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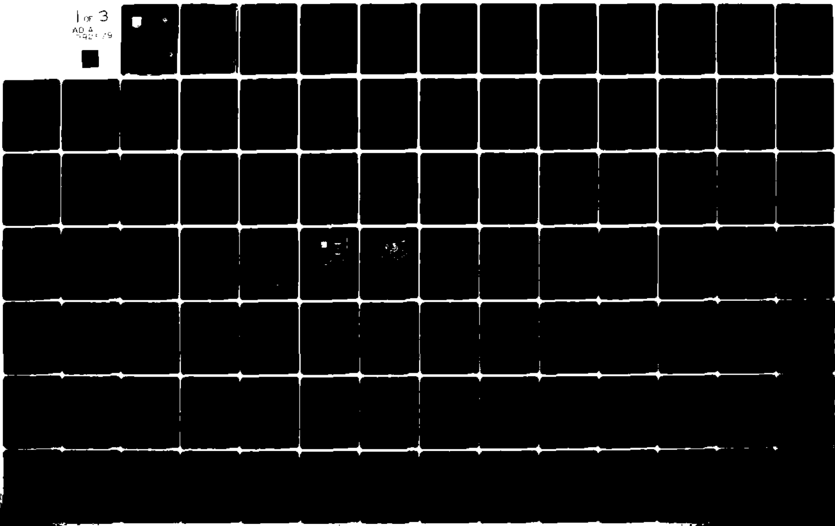

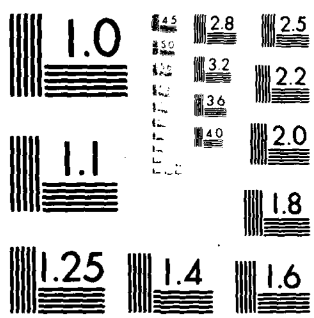

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ATMOSPHERIC TRANSMISSION AND PARTICLE SIZE MEASUREMENTS
PROCEEDINGS OF WORKSHOP: 23-25 October 1979

UNIVERSITY OF DAYTON RESEARCH INSTITUTE
300 COLLEGE PARK AVENUE
DAYTON, OHIO 45469

EDITOR: John F. Myers, ASSISTED BY: James K. Luers, William C. Smith

MAY 1980

TECHNICAL REPORT AFWAL-TR-80-1086
FINAL REPORT FOR PERIOD JULY 1979 - MAY 1980

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This technical report has been reviewed and is approved for publication.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A highly accurate description of the atmosphere in terms of its transmission and aerosol size distribution is needed to quantify the performance of various DOD reconnaissance and weapons targeting systems.

Recent DOD measurement programs have produced inconsistent data sets. Doubt has been cast upon the accuracies and sensitivities of current meteorological instruments which provide transmission and particle size data.

The purpose of the Atmospheric Transmission and Particle Size Measurements workshop ~~(Dayton, Ohio, October 23-25, 1979)~~ was to provide a forum for

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20. Abstract (Cont'd)

information exchange between people who have been involved in the measurements. A definition of the state of the art of present equipment and technique was obtained.

An overall summary, workshop session summaries, and abstracts of presentations are included.

FOREWORD

The editors would like to extend their gratitude to each of the chairmen who presided over the workshop sessions and to all the participants. Special mention must be made of the efforts by William C. Smith of the Air Force Wright Aeronautical Laboratories/Avionics Laboratory, Contract Monitor of this effort.

The technical assistance offered by the staff of the Applied Systems Analysis Section of the University of Dayton Research Institute, in particular, the organizational concern of Ms. Jacquelin Aldrich, is greatly appreciated.

All of the aforementioned contributed extensively to these proceedings and to the success of the Atmospheric Transmission and Particle Size Measurements Workshop, October 23-25, 1979, Dayton, Ohio.

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INTRODUCTION

Various Department of Defense (DOD) reconnaissance and weapons targeting systems operate in the visible and infrared regions of the electromagnetic spectrum. For these wavelengths, the atmosphere can limit the energy received by a sensor. In order to quantify the performance of such systems, a highly accurate description of the atmosphere in terms of its transmission and aerosol size distributions is needed.

Recent large-scale measurement programs by the Army (DIRT - Dusty Infrared Tests) the Navy (San Nicolas Island), and the Air Force (OPAQUE - Optical Atmospheric Quantities in Europe; Atmospheric Effects Measurement Program at The Target System Characterization Facility (TSCF), Wright Patterson Air Force Base, Ohio) have produced inconsistent data sets. Consequently, doubt has been cast upon the accuracies and sensitivities of current meteorological instruments which provide transmission and particle size data. For present DOD applications and requirements, these devices may be inadequate.

The main purpose of the Atmospheric Transmission and Particle Size Measurement Workshop was to provide a forum for information exchange between people who have been involved in the measurements. Through their interaction, a definition of the state of the art of present equipment and techniques was obtained and will be the subject of these proceedings.

The two topics, transmission and particle size measurements, were covered in four distinct workshop sessions. Manufacturers' viewpoints, measurement programs, accuracy and calibration, and new instrumentation formed the nuclei of general interest.

In each session, a panel of participants with experience in the session's topic gave presentations. Discussion was stimulated by the response of panel members and the audience. The presentations and discussions outlined the strengths and weaknesses of current measurement techniques.

An editorial summary and individual session summaries follow.

Two formally presented papers introduced the participants to workshop interest in transmission (Kaplan) and particle size (Neer) measurements. These papers appear in the appendices along with abstracts of all session presentations.

EDITORIAL SUMMARY

The editors feel that the following points, developed during the various workshop sessions, give some indication of the state of the art in atmospheric transmission and particle size measurements. Parenthetic lists of names refer to presentations summarized in the appendices.

TRANSMISSION MEASUREMENTS

Conventional transmissometry. One major workshop objective was to review and evaluate the role of the conventional, projected beam transmissometer, typified by the Barnes Engineering Company products. This workshop was by and large supportive of the conventional device. Conventional transmissometry is recognized as having definite utility for transmission research, especially in routine data acquisition.

There are, however, documented problems with such transmissometry equipment. In particular, calibration techniques (Gallery, Zweibaum), instrument electronics and receivers (Martin), and special problems of long path measurement (Gruenzel), such as turbulence and beam wander, have been discussed.

Absolute transmission. There is a demand for the more difficult measurement of absolute transmission (versus relative transmission of conventional transmissometry). The overriding rationale is that it is a more representative measurement and must ultimately be confronted in characterizing air-to-ground propagation along slant paths (Thomas, Turner).

Spectral measurements. There is a demand, on the part of the modeling community in particular, for spectral (narrow band) transmission measurements (Smith, Wijntjes, Turner).

New instrumentation. The progress of significant improvements in current instrumentation and the development of new techniques and equipment applicable to the special requirements of the DOD has been slow. Exceptions to this are lidar (Kohl) and the FLIR (Forward Looking Infrared) and video configurations (Thomas).

PARTICLE SIZE MEASUREMENTS

Conventional instrumentation. There is an abundance of particle sizing equipment applicable to many diverse needs. One practical limitation on usage is that a particular instrument is often not well understood by researchers and manufacturers alike. An analysis of Knollenberg counters (Selby and Weiser) underscores this point. The investigation indicates an effective sample area problem. That is, the sensitivity of the sampling area of a device may differ from the manufacturer's specifications. The result can often be underestimates of particle size distribution.

It appears that relevant, satisfactory measurements can be made with present counters given the following conditions:

(1) successful calibration;

(2) understanding and analysis of the particular system (e.g. delineation of the effective sample area); and

(3) understanding the particular sampling problems presented by the test aerosols (e.g. how does a laser beam affect the sample?)

Research direction. The thrust of the particle size sessions was towards equipment involved in point or local measurements of aerosol size and concentration. Point measurements may or may not represent the aerosol characteristics along a given propagation path and for this reason their usefulness may be limited. In an overview presentation (Neer), it was suggested that measurements of "bulk optical properties" (with integrating nepholometers, for instance) offer certain advantages over point measurements. It was indicated that these bulk or volumetric properties may be easier to measure and involve less uncertainty than point measurements and also may determine the optical characteristics of an atmospheric volume to an accuracy greater than that of the predictions based on the point measurements.

It would appear that research directed at these bulk optical measurements as well as their role in characterizing optical transmission would be relevant at this time.

Calibration. The outstanding deficiency regarding particle measurements and present equipment is the lack of standardized calibration criteria.

Currently, there exist neither national nor rigorous industrial standards. Moreover, inconsistencies have been found in commercially available calibration spheres (Knollenberg) and problems with commercial droplet generators are known as well (Selby). As a consequence, it is very difficult for researchers to compare results.

New instrumentation. Progress in the development of instrumentation and new sizing techniques is evident. Holographic (Gustafson, Belz) and optic-acoustic applications (Farmer) as well as new spectrometers (Dearborn, Miranda) were described. These new techniques are valuable from the standpoint of making measurements as well as corroborating the measurements of conventional instruments.

ATMOSPHERIC TRANSMISSION: MANUFACTURERS' PRESENTATIONS

PANEL

C. Vought (Lockheed), Chairman
W. Gallery (AFGL)
H. Kaplan (Barnes Engineering Co.)
R. Moulton (Night Vision Lab)
F. Smith (Optimetrics)
D. Snider (ASL)
*A. Thomas (Southern Research Institute)
*F. Zweibaum (Barnes Engineering Co.)

Session theme. Definition of the present state of the art in available transmissometry instrumentation was the session objective. Topics of discussion included operation characteristics such as measurement and dynamic range, accuracy, field use, and cost.

The panel and audience received presentations on conventional and alternative approaches to transmissometry by Messrs. Zweibaum and Thomas respectively. The salient developments of these presentations and, in particular, of ensuing discussions included the following:

Instrument requirements. Common requirements of transmissometry devices with regard to the EO sensor community's current atmospheric transmission problem are:

(1) measurement fidelity over relatively long paths (several kms);

(2) real time capability;

(3) simultaneous measurements in several spectral bands with high spectral resolution;

(4) field adaptability; and

(5) cost effectiveness.

The Barnes Engineering Company representatives were addressed as to whether or not a more uniform approach on the part of Tri-Service measurement objectives could induce a favorable (cost effective) economic situation for the DOD (Moulton). The reply (Kaplan, Zweibaum) was that it could but that the possibility of such a uniform approach was seriously doubted because of the unique requirements of each service. No elaboration on this theme nor conjecture of possible program consolidation was attempted.

*Denotes presenter.

Slant path problem. Conventional transmissometry offers a relative measurement of transmission in the sense that propagation of a known source in the real atmosphere is measured and compared to a calibrated, vacuum value. In practice, this measurement has application to horizontal paths.

Another scenario of considerable interest to DOD programs involves use of EO sensors in air-to-ground (slant path) applications. These scenarios are characterized by complex scattering processes including the scattering of sunlight into the propagation path.

It appears that the measurement of a projected beam (conventional) transmissometer will not be adequate for correlation of transmission data and signals obtained by sensors within this slant path context. A. Thomas provided a discussion of a transmissometry system composed of a detector and scanner device called a FLIR (Forward Looking Infrared). A configuration of FLIRs, to cover the various spectral bands of interest, was offered as an approach to airborne transmission measurements.

Accuracy. It was pointed out that many factors influence the accuracy of a given instrument. Specifically, some of the more critical factors include path length, spectral band, calibration uncertainties, and optics (Zweibaum).

Measurement degrading effects. Considerable discussion focused on the recognition of the measurement degrading aspects of optical turbulence, namely scintillation and beam wander and a corresponding increase in the observed phenomena with range. Much has been done theoretically in the area of atmospheric turbulence. Turbulence has a well known power spectra as well as statistical characteristics (log-normal probability distribution). However, realization of specific (averaging) techniques for practical use (per instrument per scenario) seems to be quite elusive (Vought, Levis, see abstracts for later sessions).

ATMOSPHERIC TRANSMISSION: MEASUREMENT PROGRAMS

PANEL

*J. Dowling (NRL), Chairman
C. DiMarzio (Raytheon)
*W. Gallery (AFGL)
*R. Gruenzel (AFWAL/AA)
*B. Kennedy (ASL)
*W. Martin (AFWAL/AA)
*M. Neer (SCITEC)
J. Selby (Grumman)
*F. Smith (Optimetrics)
F. Zweibaum (Barnes Engineering Co.)

Session theme. A review of past, present and proposed field measurement programs with emphasis, where possible, on equipment performance was the basic objective of this session. Discussion topics included the purpose and description of the experiment as well as certain specifics of instrument performance such as field adaptability and any special terrain and meteorological conditions affecting instrument response.

On-going and recently completed Tri-Service measurement programs were reviewed in this session. It was apparent that different problems and interests characterize the various efforts. For example:

(1) The Navy has need for horizontal, moderately long (5 km), oversea path measurements at or near the surf line. Water vapor and common marine aerosols play the major role in extinction processes and it is towards an overall identification of these effects that the Navy is inclined (Dowling).

(2) The Army must contend with both natural and artificial obscurants such as airborne dirt, dust, and smoke particulates. Test programs typically involve battlefield scenarios (Kennedy).

(3) The Air Force is interested in slant path propagation for ranges up to 8 km (Gruenzel, Martin).

Concurrent observations of relevant meteorological indices affecting optical transmission is a common thread binding the individual measurement programs.

Barnes transmissometer analysis. Martin and Gruenzel discussed results of comprehensive analysis performed on the Barnes Model 14-WP multispectral transmissometer to ascertain the feasibility of its use over an 3 km land path as part of the AFWAL/AA Atmospheric Effects Measurement program. Inherent

*Denotes presenter.

difficulties measuring transmission over this land path motivated a detailed analysis of instrument electronics, sources, receivers, and general susceptibility to beam wander and scintillation. The AFWAL/AA study concluded that the Barnes Model 14-WP transmissometer source should be adequate but a more uniform receiver would be desirable for longer path measurements.

A modeler's viewpoint. A representative voice from the modeling community (Smith) advised that there is a need for more spectral measurements as well as more communication between modelers and experimentalists. Research and EO systems development require the concerted efforts of systems planners, modelers and those responsible for providing relevant data.

ATMOSPHERIC TRANSMISSION: ACCURACY, CALIBRATION AND INSTRUMENT LIMITATIONS

PANEL

D. Snider (ASL), Chairman	*W. Porch (Lawrence Livermore)
*W. Gallery (AFGL)	*G. Wijntjes (Block Engineering)
H. Kaplan (Barnes Engineering)	*E. Wilkins (Vought Corporation)
*C. Levis (OSU)	*F. Zweibaum (Barnes Engineering)

Session theme. Evaluation of instrument performance relative to design specifications was the overall objective of this workshop session. Discussion topics were to include calibration techniques and instrument precision (repeatability), accuracy, measurement thresholds and dynamic range as well as deficiencies.

Among the motivations for concern about the validity of transmission measurements were the results of intercomparisons with OPAQUE transmissometers. Significant discrepancies (up to 16%) were discovered during these tests between European and AFGL transmissometers. It was indicated that the differences were due to the receiver systems. The differences were not eliminated with the Barnes calibration technique. To standardize the OPAQUE IR transmissometers, a (temporary) "calibration" was performed against the calculated transmittances from LOWTRAN for high transmittance (∿100%) conditions (Gallery). The situation reflects the critical nature of calibration considerations. Moreover, the state of the art of transmission measurements is characterized by lack of sufficiently reliable calibration procedures.

Calibration. A detailed description of the Barnes Engineering Company's calibration technique was presented (Zweibaum). Problems with maintaining a sufficiently hot IR source (1000°F) have posed difficulties. Replacement with a more stable but cooler source has resulted in a reduction of S/N.

The Barnes Engineering Company does not claim complete satisfaction with their calibration technique but does maintain that it is the most appropriate procedure developed to date and welcomes any further suggestions or alternatives.

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*Denotes presenter.

Spectral measurements. The need for high resolution measurements was underscored (Wijntjes). The point was taken that, where possible, transmissometry equipment should be designed for the highest spectral resolution feasible. The results can later be degraded for a specific application.

Meteorological effects. Digressing somewhat from the session's intended themes, several interesting discussions of meteorological effects on sensor measurements and electromagnetic propagation were presented.

Work done in the San Francisco Bay area at Lawrence Livermore (Porch), in conjunction with optical techniques of pollution monitoring, has indicated that inversion strength and height are usually the dominant meteorological parameters related to extinction processes in the visible region. It was noted that small variations in the inversion height can often result in large differences in atmospheric transmission.

Another meteorological phenomenon whose role perhaps has not been fully recognized is that of atmospheric moisture content and its high variability. Monitoring this quantity via solar radiometry, it has been concluded that the effects of fluctuating precipitable water (PW) content on atmospheric transmission can be significant (Wilkins). In addition, changes in PW may occur during seemingly benign, high visibility conditions so that the phenomenon might easily go unobserved. It was noted that transmission models do not consider this parameter. Differences in measured and calculated transmission may be due, in some part, to this moisture variability.

Research direction. Though only indirectly related to the overall session topics. the question arose as to what types of measurement and corresponding research should be emphasized in the near future: (long) horizontal or slant path transmission.

It was observed that given present instrumentation. trends seem to be towards longer path transmission. The necessity for such measurements lies in current transmission modeling efforts and their consequent validation. To this end, accuracy and reliability should be the main concern of present long path (>8 km) propagation measurements. Furthermore, it was noted that the first step in comprehensive atmospheric transmission research should be that of proceeding with and refining the accessible: the horizontal path

problem is simpler than the slant path case. Anticipated scenarios (for Army and Navy) would certainly appear to involve the horizontal path so that this philosophy would not be irrelevant.

ATMOSPHERIC TRANSMISSION: NEW INSTRUMENTATION

PANEL

W. Smith (AFWAL/AA)
*C. Bruce (ASL)
*M. Gannon (MRI)
F. Gibson (Lockheed)
*R. Kohl (UTSI)
I. Tang (Brookhaven)
*R. Turner (SAI)
A. Williamson (SRI)

Session theme. The presentation of new instrumentation and techniques in the field of transmission measurements was the theme for this final session. Discussions of measurement objectives, instrument characteristics and field adaptability were included.

Equipment discussed included the following:

Spectrophone. Application of spectrophones to aerosol measurements has been investigated over the past several years to certain advantage. The spectrophone measures the absorption coefficient of a given aerosol and seems best suited for research in which components of extinction, scattering, and absorption are needed (Bruce). However, as a point measurement, its usefulness for the atmospheric transmission problem would seem limited.

Telephotometer. A new instrument for long path visible contrast determination useful to meteorological research is in production by MRI and was described (Gannon). The technique makes an "absolute" measurement in that it takes into account light scattered into and out of the optical path. The instrument operates in the visible part of the spectrum and performs best under "fair weather" situations where the sky is cloud-free and path illumination is uniform.

Lidar. A measurement technique using lidar was presented (Kohl). The technique offers considerable promise for the slant path transmission measurement problem. An attractive advantage of lidar is the lack of necessity for airborne instrumentation. Difficulties with the interpretation of these measurements as well as a seemingly intrinsic lower limit of measurable transmission are possible drawbacks.

*Denotes presenter.

Contrast Transmittance. A comprehensive contrast transmittance model was outlined (Turner). The instrumentation that the proposed model requires includes devices to measure liquid water content, particulate mass column density, and solar radiance. Possibly most important is the perceived need for narrow band transmissometers with variable beam width capability.

C_n^2 detector. Turbulence effects due to temperature induced fluctuations in the refractive index of the atmosphere are statistically described by the quantity C_n^2, refractive index structure constant. This quantity measures the strength of atmospheric turbulence. A scintillation type C_n^2 detector and its current application at Redstone Arsenal were reviewed (Vought). In this technique, a known source radiates over a given path. As optical turbulence increases over the path, fluctuations appear at the receiver. Software processing of these fluctuations affords a determination of average C_n^2 along the path.

PARTICLE SIZE: MANUFACTURERS' PRESENTATIONS

PANEL

J. D. Hunt (AEDC), Chairman
*J. Agarwal (TSI)
M. Farmer (UTSI)
*S. Kinsman (Coulter)
*J. Knollenberg (PMS)
*A. Lieberman (Royco)
W. Montgomery (Lockheed)
C. Stanforth (G.E.)

Session theme. Definition of the present state of the art in available particle sizing instrumentation was the session objective. Topics of discussion included operational characteristics such as measurement and dynamic range, accuracy, field use, and cost.

For EO sensor performance characteristics, particle counters measure both size (diameter) and concentration of atmospheric particles. These data have direct application to transmission modeling. Contemporary efforts to improve, validate, and extend these models have necessitated development and refinement of sizing devices in general.

Commercial particle sizing instruments. A variety of measurement principles were discussed including the following:

(1) The light scattering and light extinction families of Knollenberg counters.

(2) A conductive liquid displacement laboratory technique: the Coulter Counter.

(3) Royco counters.

(4) Nuclear counters using condensation techniques and electrical aerosol sizers (inferring size from a measurement of particle mobility resulting from an imparted electrical charge), both by TSI.

Measurement degrading effects. A few common problems which tend to degrade the accuracy of particle counters were noted.

(1) Position dependence (Knollenberg). Due to variability of particle trajectories within the sample volume, measurements may often underestimate the counts of smaller particles. These particles tend not to be seen away from the middle of the viewing field.

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*Denotes presenter.

(2) Particle clusters (Knollenberg, Lieberman). Coincident drops are not discriminated and tend to cause uncertainty in the measured distribution.

PARTICLE SIZE: MEASUREMENT PROGRAMS

PANEL

*E. Burgess (Dugway), Chairman	A. Lieberman (Royco)
L. Crouch (AFWAL/AA)	*M. Maddix (Redstone)
*M. Farmer (UTSI)	*H. Miranda (Epsilon Labs)
*J. D. Hunt (AEDC)	F. Niles (ASL)
J. Knollenberg (PMS)	*G. Trusty (NRL)

Session theme. A review of past, present and proposed field measurement programs with emphasis, where possible, on equipment performance was the basic objective of this session. Discussion topics included the purpose and description of the experiment as well as certain specifics of instrument performance such as field adaptability and any special terrain and meteorological conditions affecting instrument response.

Tri-Service measurement. A wide variety of particle sizing applications was indicated, for example:

(1) The Navy has an interest in making in situ measurements of marine aerosols under high humidity (80%+ R.H.) conditions (Trusty).

(2) The Army has an interest in both field and laboratory measurements. Field measurements include those of smoke (Farmer) and other battlefield obscurants (Maddix). Laboratory smoke measurements support the field experiments.

(3) The Air Force is involved in diverse field and laboratory measurement programs. OPAQUE seeks to characterize aerosol effects on optical propagation in the European environment (Gallery). There is interest in laboratory research of icing clouds (Hunt). Finally, determination of the chemical constituency of the stratosphere has been approached through the use of balloon-borne spectrometers (Miranda).

Accuracy. There is concern that the accuracy of in situ measurements using conventional particle counters is limited by, roughly, a factor of two (Trusty). It was also pointed out that without careful definition of the sizing bins, measured distributions can be misleading (Farmer).

Several pertinent summary comments were offered by the Chairman.

(1) There is a need for communication between experimenters and instrument manufacturers.

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*Denotes presenter.

(2) Calibration to the real world continues to be a problem.

(3) As the variety of applications would imply, no single instrument or technique can be expected to satisfy all requirements.

PARTICLE SIZE: ACCURACY, CALIBRATION AND INSTRUMENT LIMITATIONS

PANEL

*J. Selby (Grumman), Chairman
*J. Agarwal (TSI)
*R. Belz (SVERDRUP/ARO)
D. Duncan (Pacific Sierra)
*W. Gallery (AFGL)
*S. Gustafson (UDRI)
*J. Knollenberg (PMS)
A. Lieberman (Royco)
R. Melke (Monsanto)
*H. Miranda (Epsilon Labs)
F. Niles (ASL)
C. Weiser (Grumman)

Session theme. Evaluation of instrument performance relative to design specifications was the overall objective of this workshop session. Discussion topics were to include calibration techniques and instrument precision (repeatability), accuracy, measurement thresholds and dynamic range as well as deficiencies.

Presentations pertinent to session objectives were augmented by a review of (calibration) particle generation techniques (Agarwal) and discussions of the application of holography to particle sizing (Belz, Gustafson).

Calibration. Measurement accuracy of size and concentration ultimately depends on instrument calibration. A problem recognized by both manufacturers and experimentalists is the lack of standard size particles and the subsequent uncertainty for work with any particle sizing equipment. For example, J. Knollenberg cited a study by Porstendorfer which revealed discrepancies between the measured and specified diameters of commercially available "standard" spheres.

Sampling Area. Actual sampling areas of commercial particle counters can differ from the manufacturer's specifications. The extremities of the sampling areas are of particular concern. One consequence of this situation is that a bias may be introduced: small particles are not "seen" near the edges whereas larger particles are visible throughout.

Closely related is the observation that instrument channel excitation is often a function of particle orientation and position within the sampling areas as well as of particle size.

*Denotes presenter.

The Selby-Weiser analysis of two Knollenberg devices illustrates these problems. One of their conclusions for the Optical Array Probe* draws attention to a potential underestimation of (particle) number density by as much as a factor of two.

H. Miranda suggested a possibly useful parameter for assessing the severity of some of these effects, namely, the spread function. A comparison of the observed instrumental spread function with the system spread function can provide an indication of the presence of errors due to the above effects.

Sampling Techniques. Measurement of particles involves collection processes. The question as to whether the traditional chamber sample represents the ambient volume is critical to valid measurement of both particle size and concentration. A manufacturer (J. Knollenberg) advised caution with particular regard to the following:

1. Was the volume affected by exposure to the (measuring) beam?

2. Was a bias towards or against the larger-heavier particles introduced, for instance by ignoring isokinetic considerations?

Accuracy. One presentation (J. Selby) provided evidence of the accuracy of a commercial counter. Tests at Grumman on a Knollenberg Optical Array Probe indicated that manufacturer's size tolerances were met in all cases as well as recorded counts to within two percent of measured values.

*The use of trade names in this report does not constitute an official endorsement or approval of the use of such commercial hardware or software. This report may not be cited for purpose of advertisement.

PARTICLE SIZE: NEW INSTRUMENTATION

PANEL

*M. Farmer (UTSI), Chairman
*F. Dearborn (AFGL)
A. Lightman (UDRI)
V. Macias (Kirtland, AFB)
P. Monfette (Holloman, AFB)
*D. Roberds (ARO)
*C. Stanforth (G.E.)

Session theme. The presentation of new instrumentation and techniques in the field of particle size measurements was the theme for this final session. Discussions of measurement objectives, instrument characteristics and field adaptability were included.

Recent developments in instrumentation presented at this time included the following:

Interferometry Sizing. Oscillations in scattered light caused by particles passing through interference fringes of a split beam can be observed with particle size and concentration inferred. D. Roberds described a particular laser interferometer designed by the Arnold Engineering Development Company.

The present technique is limited to particles large enough to scatter the interference pattern (~5 μm). Calibration is achieved by using glass beads measured, for instance, microscopically.

Sizing Spectrometry. Current and proposed sizing spectrometers of AFGL/Epsilon Laboratories provide unique capability in that they not only detect and size but also provide a means for the spectral analysis and chemical identification of individual aerosol particles. F. Dearborn presented a discussion of such spectrometers. He noted that the determination of chemical constituency is ultimately related, through refractive index and scattering, to transmission measurements. As a consequence, this type of device may play an important role in the correlation of in situ ground measurements of aerosol size distributions with optical transmission.

Laser Velocimeter. A laser velocimeter offers an optic-acoustic approach ideally suited for smoke stack measurements. M. Farmer gave a brief discussion

*Denotes presenter.

of this technique which uses a laser to drive particulates within a chamber. An acoustic signal is simultaneously monitored for frequency lags and particle sizing can be accomplished.

Since there are numerous technological applications, besides those of the DOD community, which require particle sizing techniques, an overview of current industrial involvement in particle sizing was presented with an eye towards possible adaptation to DOD needs.

Industrial applications of particle sizing. Jet engine manufacturers have critical measurement needs with regard to engine inlet measurements and spray (fuel) nozzle design. It was indicated that accurate droplet sizing as well as concentration and spatial distribution of particles in the 10-200 μm range are typical problems encountered in design and evaluation of engine performance (Stanforth). Furthermore, engine emissions of both smoke and gaseous nature must be well characterized for future research efforts.

Particle sizing needs of gasoline and diesel engine manufacturers for meeting emission standards as well as for engine performance evaluation were described (Farmer). An optic-acoustic technique used at the General Motors Labs (Warren, Michigan) to measure diesel soot was mentioned.

In his summary presentation, M. Farmer emphasized several points relevant to particle sizing in general.

Calibration. There is a definite need for particle sizing standards. The National Bureau of Standards does not have any current standards, although a program has just begun which should coordinate work in this direction.

Typically, optical counters give particle size and concentration in terms of spherical calibration particles. Oddly or imperfectly shaped calibration "spheres" can produce misleading measurements.

Reliability. Often, concentration measurement reliability for a given instrument may be checked by dyeing a test aerosol or using a radioactive tracer and measuring the collected amount independently of the counter. This value may then be compared with the instrument's expectation to give some indication of reliability.

The following pages attempt to give some representation of the subject matter developed by contributing participants. Hopefully, these pages will afford the reader a reasonably brief but accurate idea of the state of the art of atmospheric transmission and particle size measurements.

It was not the desired intention to conduct a formal technical exchange and, accordingly, the summaries do not pretend to be comprehensive.

The editors acknowledge full responsibility for the wording of all abstracts of presented material. These were constructed from relevant view-graphs used by the presenter, notes by UDRI personnel, solicited summaries and an occasional, submitted paper. A sincere attempt was made to faithfully record information pertinent to workshop themes.

APPENDIX A

TRANSMISSION PAPERS

HISTORY AND PRESENT STATUS OF INSTRUMENTATION FOR MAKING INFRARED ATMOSPHERIC TRANSMISSION MEASUREMENTS

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INTRODUCTION

The need for measuring the transmission of the atmosphere in the infrared arose because man, blind in the infrared, needed this information for several tactical reasons. These include signature characterization of ordnance and ground vehicles through the atmosphere and the effect of man-made and natural contaminants on these signatures as well as on the operation of night vision and image enhancement devices, on the performance of heat-guided weapons and on the effectiveness of countermeasures.

Defining the infrared thermal signature of military ground vehicles for example, involves determining the vehicle's self-emitted radiation after this infrared energy has traveled through a length of atmosphere on its way to the detection system. In the course of this transmission, radiation is absorbed and scattered by atmospheric constituents, by the contaminants normally present under battlefield conditions, and by additional contaminants that may be introduced deliberately to confuse identification by thermal signature. The atmosphere and the man-made contaminants alter the vehicle's self-emitted radiation in a manner that is grossly non-uniform with wavelength and which seriously impedes the collection and use of vehicle thermal signatures.

Methodical collection of signature information should include an accurate evaluation of atmospheric spectral attenuation at the location and time of the data collection. This permits atmospheric attenuation effects to be removed from the signature data. Moreover, in the case of evaluating the performance of tactical signature analysis equipment, it permits a standard performance factor to be assigned to the system itself. With the availability of such performance factors, the effects of development work can be compared realistically.

Also of significant importance is the need for establishing phenomenological characteristics at different geographic locations. Once statistical determinations of atmospheric conditions are made at a particular site, it should then be practical to predict the performance of different systems at the location. As such information is being collected, a valuable contribution will be made to the establishment of a more general atmospheric model that will more successfully relate atmospheric transmission to meteorological and climatic conditions.

This paper will discuss the basic physical laws involved in these measurements, describe some of the measurement systems that have been manufactured and trace the historical development of these systems.

THERMAL RADIATION EMITTED BY TARGETS

Target thermal radiation from targets of solid materials generally approximate a blackbody characteristic. The peak wavelength is a function of target temperature and the energy is spread over a broad spectrum. For practical targets, the usable energy is roughly in the region from 1-14 micrometers. For gaseous targets such as exhausts, flames, flares, etc., the radiation is highly spectrally selective, corresponding to the natural emission bands of the gases involved. It is generally restricted to the region shorter than 5 micrometers.

ATMOSPHERIC TRANSMISSION

Atmospheric transmission is also highly spectrally selective, as shown in Figure 1.

The most important energy absorbers are water vapor, carbon dioxide, and ozone. The spectral regions in which these absorb are shown in the atmospheric spectral transmission curve. Other important absorbers are nitrous oxide, carbon monoxide and methane.

In addition to atmospheric absorption, radiation may also fail to reach the receiver because it may be deflected from its path by droplets of water in the form of haze, fog or clouds which cause considerable loss by scattering. Other sources of attenuation are man-made contaminants, such as smoke, which might be deliberate.

Prior to 1969, in an effort to assess atmospheric effects, extensive observations were made by virtually every military installation engaged in developing and testing systems employing long range detection of thermal radiation. Although a number of transmission laws and empirical relationships were established, it was evident that atmospheric radiation spectral transmission has a very complex structure and that the details of this structure vary considerably with location and meteorological conditions. To many, it was becoming clear that the only accurate method of determining atmospheric transmission characteristics was to measure at the time and place of the test.

Early equipment was assembled using an assortment of laboratory devices not suitable for continuous field use. Clearly a practical, reliable field system was needed. Our company has been concerned with this problem since 1970 together with military personnel involved in developing various types of radiation detection systems.

Our first atmospheric transmissometer system designed for field deployment was initially developed to meet this need, partly in response to requirements from the U.S. Army, Night Vision Laboratory (NVL). It consists of a source assembly and a receiver assembly, deployed at opposite ends of the atmospheric path of interest.

In typical field installations, the source assembly and receiver assembly are mounted either on unsheltered fixed platforms, or in the rear of truck

vans or converted recreational vehicles. These are then located so atmospheric transmission measurements can be made at the distance and locations required to support the military systems tests being conducted. The basic arrangement is shown in Figure 2. Our earlier systems were based on our standard field spectroradiometer as a standard chopped collimated source.

In order to establish parameters for optimum operation the initial system was designed for maximum flexibility of operation. The receiver included two separate liquid nitrogen cooled sensing heads and the receiver control unit included a number of signal output terminals drawn from various stages in the signal processing circuits. The initial system was delivered to NVL and field tested at Fort Hood, Texas.

As a result of the tests a standard-dedicated system designated 14-708 was conceived and, after field tests at NVL, production units were provided throughout the tri-service group and to the NATO participating governments. In the 14-708 the source assembly or infrared search light contains a conical blackbody radiator controlled at a temperature between 500°C to 1000°C. Also contained in this assembly is a reflective collimator to concentrate the radiation in one direction. This projects a high level of energy to the distant receiver, and permits 1 km operation with better than a 100 to 1 signal-to-noise ratio. At the receiver, the diameter of the infrared searchlight beam is 30 feet for a 1 km range, greatly easing system alignments. To permit the receiver to differentiate source radiation from the background and other sources, a modulator chops or interrupts source energy as it enters the collimator. A signal pickup on the modulator generates a 90Hz reference signal used in processing the signal in the receiver . This synchronizing pickup signal must be available to the receiver either from a long cable, telemetry system, or a phase locked loop circuit in the receiver itself. Figure 3 shows the Model 14-708 system with the source assembly at the left.

The receiver assembly contains everything necessary to receive source radiation and automatically measure its transmission in four selected wavelength regions, and display the results. This is accomplished by a filter radiometer optical head, and an electronics processing unit. A timer determines the intervals between samples.

Contained in the electronics unit are circuits for amplifying and processing the signal from the optical head and for displaying and recording it in terms of percent transmission. Additional indicators on the front panel show the receiver is receiving the modulation synchronizing signal from the source, and that the source collimator and receiver optical head are in proper alignment. A close-up of the receiver electronics, showing the printer is shown in Figure 4. The receiver is calibrated to read 100% with no atmosphere when the source and receiver are in close contact. It then reads transmission directly in percentage.

Later models have extended both the range and the spectral coverages shown in Figure 5. Large diameter receiver optics and then collimator diameters up to 16 inches improve signal level. Cryogenically cooled detectors improve receiver sensitivity by a factor of as much as 10 in the 8 - 14μm region and a factor of approximately 100 in the 3 - 5μm region. The VRL system adds a visible tungsten source (as shown in Figure 6 , and looks

at the source simultaneously with three separate receivers. Finally, addition of a circular variable filter instead of discrete filters gives greater spectral resolution over the whole band.

The success of the Model 14-703 System led to the development of a more advanced system that would permit the use of an interchangeable set of infrared detectors and matching preamplifiers and thereby achieve improved spectral sensitivity in selected regions. In addition, it was deemed desirable to incorporate sufficient microprocessor control and data processing to enable the system to be used in research designed to normalize out the effects of the atmosphere and produce a spectral signature of only the target of interest. Under microprocessor control, the transmissometer became one of the operating modes of Model 12-550 Mark II Spectral Radiometer that had interchangeable modular components in both its optical and electronic systems. A photograph of the system is shown in Figure 7. The incorporation of microcomputer control as the basis of system architecture made possible the combination of transmissometer and radiometer functions in an instrument with common basic components.

The system consists of an Optical Head and a Programmable Control Unit (PCU). Both are modularized for cost-effective functional flexibility.

The optical head has available a variety of interchangeable collecting optics as well as a processor-controlled chopper, a programmable filter wheel, and modular detector-preamplifier units.

Modularity is also incorporated in the programmable control unit which contains all the circuits necessary to process the signal from the optical head according to the requirements of the applications. Rapid modification to the needs of specific applications is aided by the use of a circuit board rack with provisions for mounting up to 16 individual circuit boards. Most signal processing is done digitally, although analog outputs are also offered as a convenience.

Four powerful capabilities result from the use of a microprocessor at the base of system architecture. One, it provides such basic system functions as automatic switching of electrical attenuators, selecting chopper speed, and controlling the operation of the spectral filter system, scanning mirrors and accessory devices. Two, it provides the capabilities of automatic gain control, sample averaging and normalization. Three, it integrates the first two capabilities to the needs of the applications. Four, it conditions and processes input and output data to achieve interfacing with the selected computer and data display facilities. These capabilities are provided mainly by software which integrates system operation and adapts it for use as radiometer, transmissometer, process control system, or reflectometer.

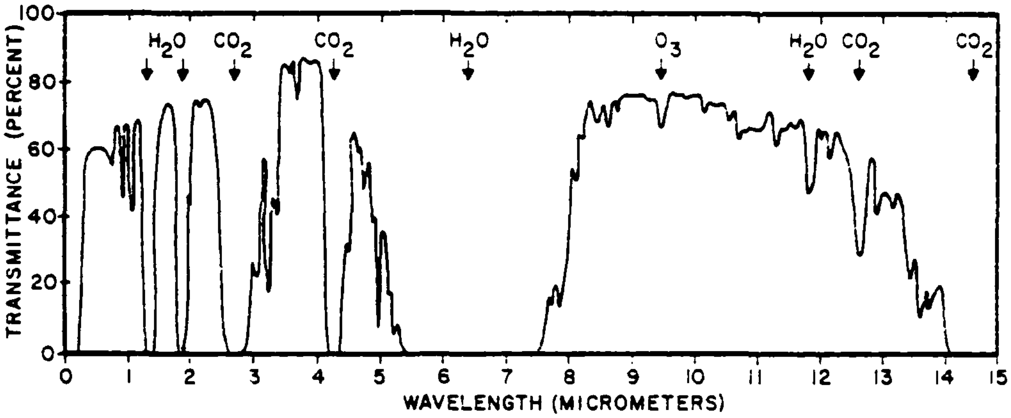

Figure 1. Atmospheric transmission of radiation at wavelengths to 15μm. Arrows identify some spectral regions in which water, carbon dioxide and ozone cause significant transmission loss.

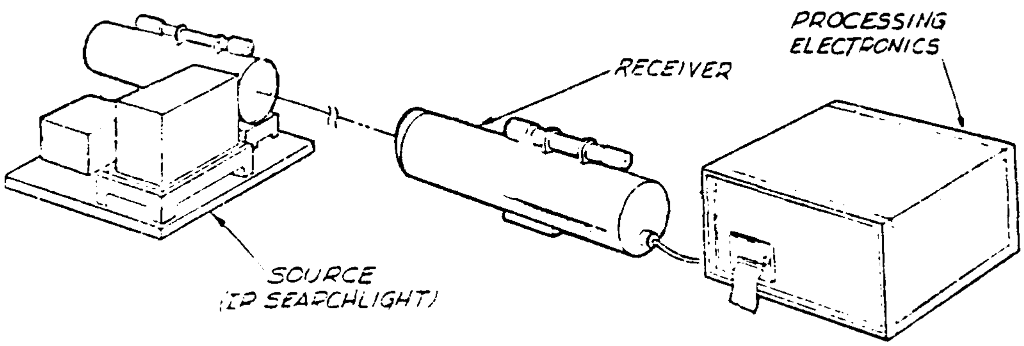

Figure 2. System Deployment for Model 14-708 Atmospheric Transmission Measurement System.

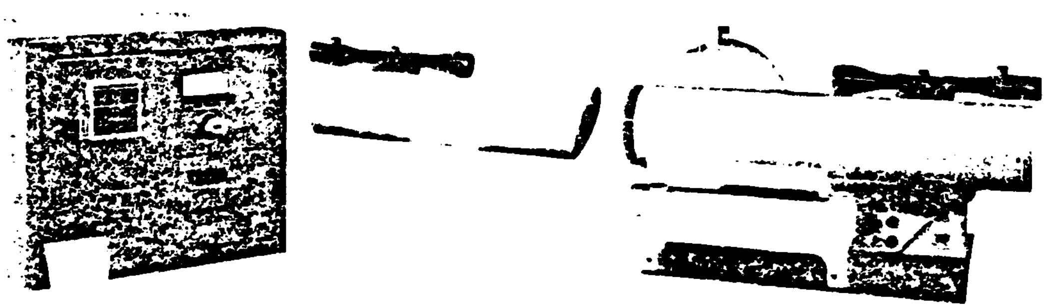

Figure 3. Model 14-708 Atmospheric Transmission Measurement System

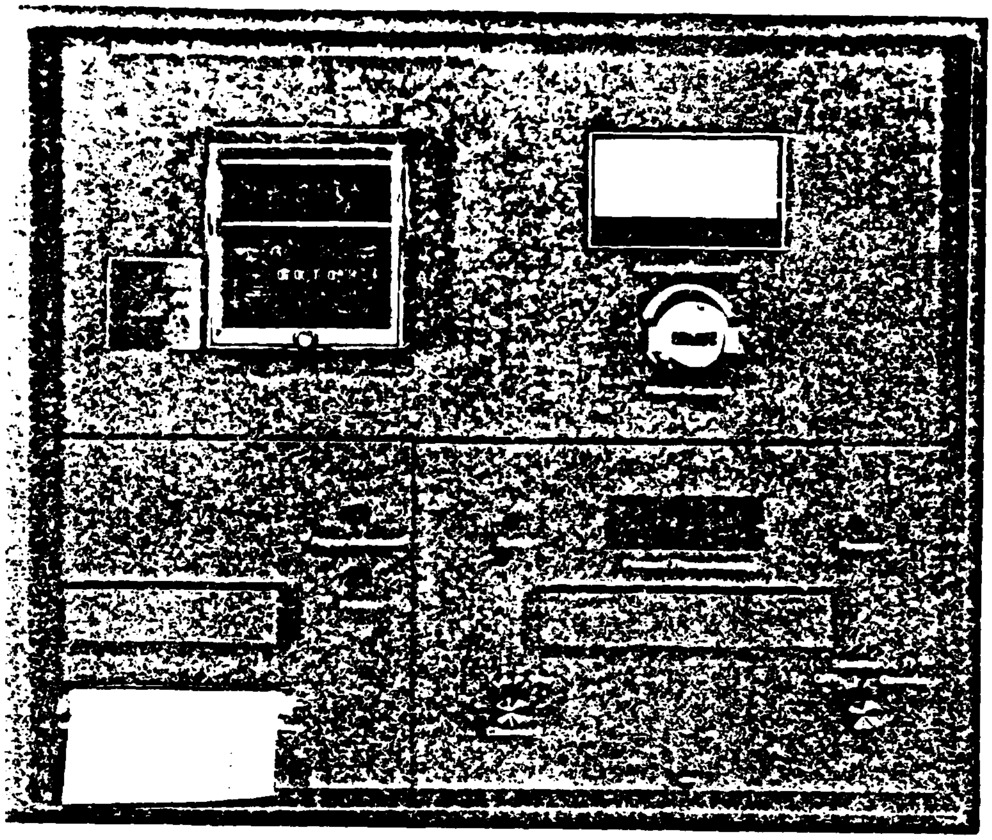

Figure 4. Close-up View of Receiver Electronics Unit.

	MODELS				
	14-708	14-708VRL	14-709	14-710	14-711
Receiver Optical System	3.6" diameter lens	4.25" diameter mirror telescope	4.25" diameter mirror telescope	4.25" diameter mirror telescope	4.25" diameter mirror telescope
Detector	Uncooled	Uncooled or Cooled	Cooled	Cooled	Cooled
Source	1000°C Blackbody	1000°C Blackbody and visible tungsten	Visible tungsten	1000°C Blackbody	1000°C Blackbody
Collimator	4.7" diameter	4.7" diameter	16.5" diameter	16.5" diameter	16.5" diameter
Spectral Region	3-5 m 8-14 m	0.5-0.7 m 3-5μm 8-14μm Simultaneously	0.4-0.7 m	8-14μm	3-5μm
Operating Range	[illegible]	5Km	8Km	[illegible]	[illegible]
Special Features		3 Heads & 3 electronics in simultaneous operation	[illegible] spectral resolution	[illegible] spectral resolutions	[illegible] spectral resolution

[illegible]

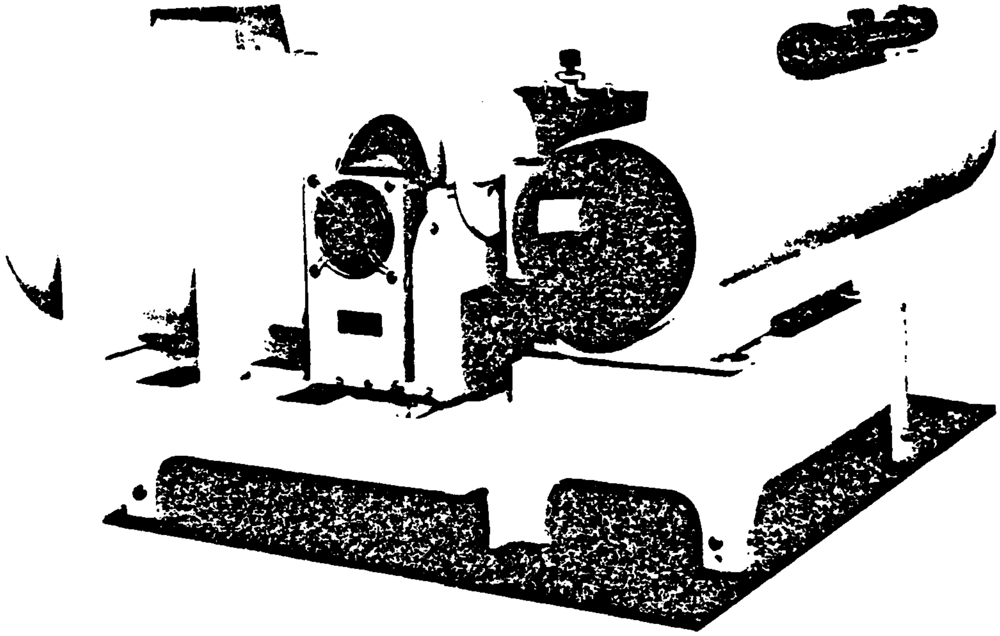

Figure 6. Radiation transmitter assembly showing infrared source (left), visible source (center), and collimator (right).

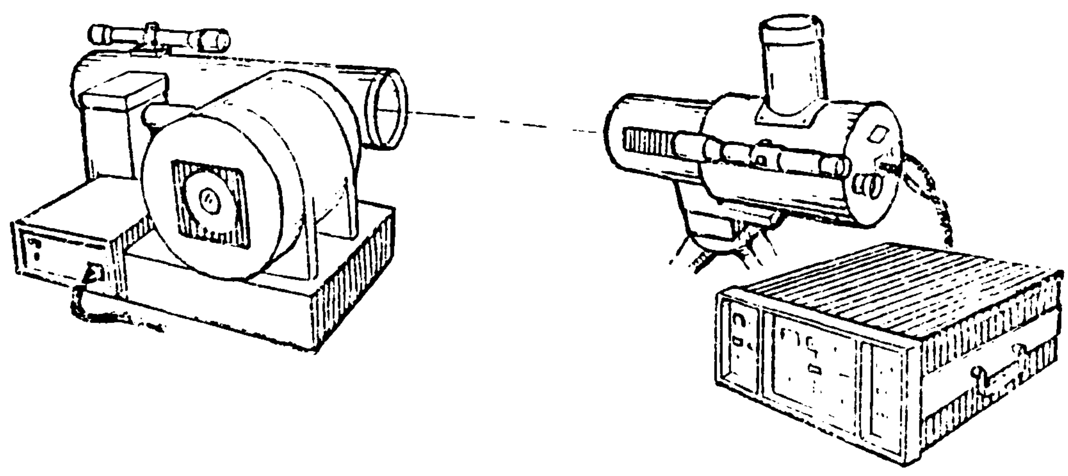

Figure 7. Atmospheric Transmissometer Configuration of Mark II System

NEW DEVELOPMENTS IN ATMOSPHERIC TRANSMISSOMETER SYSTEMS

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BASIC REQUIREMENTS FOR MODERN TRANSMISSOMETERS

The most basic requirement is that the instrument be capable of making measurements in a selected wavelength region at ranges of at least 500 meters, and that these measurements be made easily, accurately and comprehensively at the time and place when testing, for example, a military system of interest. Next is the requirement that instrument output be expressed directly and numerically in percentage transmission, to completely eliminate the complex or expensively computerized procedure required to derive the results. It is also considered important that measurements be made in at least two and preferably three of four wavelength regions of specific interest to the tests being performed. The final practicality of the system would be determined by its ease of setup and its ability to produce continuous and immediately interpreted results while in essentially unattended operation.

The Barnes Engineering Company Model 14-708 Atmospheric Transmissometer system that was developed meets these requirements and has additional features that aid its use. It consists of a source assembly and a receiver assembly. In typical field installation, the source assembly and receiver assembly are mounted either on unsheltered fixed platforms, or in the rear of truck vans or converted recreation vehicles. These are then located so atmospheric transmission measurements can be made at the distances and locations required to support the military systems tests being conducted.

Applications have validated the concept and basic arrangement of the Model 14-708 System and have pointed out the need for new developments that will be described.

NEW REQUIREMENTS

Success in a wide range of atmospheric transmission measurement applications has led to the request for more advanced capabilities which are listed below and analyzed in more detail in the sections that follow.

1. The ability to make real-time measurements over a wide spectrum with high spectral resolution.

2. The ability to make absolute radiometric measurements while transmission measurements are being made. Associated with this dual requirement are the abilities to make target emissivity or reflectivity measurements while measuring transmission.

3. The ability to make long term automatic measurements with detailed filter programming with no operator attention.

4. The ability to produce data output and accept control signal inputs that will interface with present day data transmission, processing, recording and computer systems.

5. The ability to incorporate such data processing techniques as automatic gain control, sample averaging, and normalization to remove the effects of steady-state transmission attenuation effects.

6. The ability to collect thermal signature information of military targets in spite of the radiation absorption and scatter produced by atmospheric constituents, by the contaminants normally present under battlefield conditions and by additional countermeasures that may be deliberately introduced to confuse identification by thermal signature.

7. The ability to assist in the development of battlefield countermeasures to interfere with the location and identification of military targets.

NEW INSTRUMENT CONFIGURATION

The Mark II System

The need for the abilities that have just been listed led to the development of a more advanced system that would permit the use of an interchangeable set of infrared detectors and matching preamplifiers and thereby achieve improved spectral sensitivity in selected regions. In addition, it was deemed desirable to incorporate sufficient microprocessor control and data processing to enable the system to be used in research designed to normalize out the effects of the atmosphere and produce a spectral signature of only the target of interest. Under microprocessor control, the transmissometer became one of the operating modes of Model 12-550 Mark II Spectral Radiometer that had interchangeable modular components in both its optical and electronic systems. The incorporation of microcomputer control as the basis of system architecture made possible the combination of transmissometer and radiometer functions in an instrument with common basic components.

The following characteristics have been built into the basic system to provide these field measurement capabilities: (1) high sensitivity; (2) fast response; (3) full spectral coverage; (4) automatic operation; (5) direct interfacing with data logging systems; (6) quick look capability; (7) adaptability for different operational modes and wavelength regions; and (8) elimination of steady state signals and instrument calibration constants by normalization techniques.

To demonstrate the basic capabilities of the new atmospheric transmission measuring system in performing these functions, a series of laboratory tests have been conducted. In the laboratory, the absorption signatures of a variety of smokes have been measured through test chambers on the order of from 1 to 10 feet with the effects of all other materials in the optical path being normalized out. It is desirable to repeat these measurements under dynamic field conditions at ranges from 0.5 to 3 km.

The normalization function is shown in Figure 1. The procedure begins by setting the radiation source at 1000°C and making a spectral scan through the wavelength region from 2.5 to 14.5 micrometers. Trace "A" is the result of this scan and is the familiar spectral distribution from a 1000°C blackbody together with the absorption caused by the CO_2 and H_2O in the intervening atmosphere. Note that there are straight-line horizontal sections shown in the output trace. These are due to mechanical gaps between the seconds of the continuously variable filter (CVF) in the optical head. There is no gap in the wavelengths covered.

Trace B shows system output from the same source through the same intervening atmosphere. However, the system is now normalized for the effect of the blackbody radiation curve and the absorption of the intervening atmosphere. The result is an essentially straight line at the 100 percent level.

In Figure 2, Trace A, the transmission tube is filled with nitrogen at a pressure of 1 psi above atmosphere and the trace shows only the absorption of the tube windows and nitrogen. In Trace B the absorptions in Trace A are normalized out; the residual dips or high noise level sometimes remain in regions of very high absorption.

Figure 3 shows spectral scans with 1.03 and higher concentrations of CO_2 gas along with the effects of the blackbody source, transmission tube windows and nitrogen all normalized out. Since the computer can be programmed to solve Beer's Law of atmospheric transmission, and since the path length is known, the concentration of the gas in the chamber can be monitored continuously. Similarly, the system can distinguish between different gases by their specific spectral signatures.

Figure 4 shows the spectral signature of fog oil in the test tube with all other effects normalized out. At t=0, the concentration was 0.5 gram per cubic meter. The other traces were made of successive five-minute intervals to show decreasing concentration with time.

Figure 5 shows the spectral signature of red phosphorous smoke in the concentration of 0.7 gram per cubic meter with all other effects normalized out. These two illustrations show the capability of the system to be programmed to identify battlefield smoke.

SIMULTANEOUS MEASUREMENTS OF EMISSION AND TRANSMISSION

Principle

It is desired to make simultaneous measurements of smoke transmission and smoke self emission. This can be accomplished with a 12-550 MK II instrument system set up for simultaneous radiometric and transmissometer modes. This can be done by chopping both the radiometer/receiver and the [illegible] source. With the source chopper closed, the radiometer will see background radiation plus smoke emission. With the source chopper open, the radiometer will see background and smoke emission plus source radiation attenuated by the smoke and [illegible]

It is planned to chop the radiometer at 1000 Hz and the source at 100 Hz. Therefore, the chopper open and chopper closed signal data will arrive at the 100 Hz rate. With the CVF set up to scan at 2 sec/spectrum, we will have approximately two chops per spectral point.

Data Analysis

A few definitions and equations will help to make the matter clear. Let us define the following.

T = Calibrated Source/Collimator Emission

B = Background Emission

S_e = Smoke Emission

t_a = Atmospheric Transmission

t_s = Smoke Transmission

With no smoke, and the source chopper closed, we are looking only at background

$$V_1 = Bt_a \quad . \qquad (1)$$

With the source chopper open, we see background plus source

$$V_2 = (B + T)t_a \quad . \qquad (2)$$

With smoke present we will see smoke emission plus smoke transmission with and without the source

$$V_3 = Bt_a t_s + S_e t_a \quad . \qquad (3)$$

$$V_4 = (B + T)t_a t_s + S_e t_a \quad . \qquad (4)$$

We desire to solve for t_a, t_s, and S_e. We, of course, know the calibrated source T. The calibration signal V_c, from the known source can be established originally by a close-up measurement with no atmospheric path. We then find that:

$$t_a = \frac{V_2 - V_1}{V_c} \quad .$$

$$t_s = \frac{V_4 - V_3}{V_c\, t_a} = \frac{V_4 - V_3}{V_2 - V_1} \quad .$$

$$S_e = \frac{V_4 - V_2 t_s}{t_a} \quad .$$

It is seen that proper computation from the measurements can give all desired values.

REFERENCE

Rolls, William (Barnes Engineering Company), "Two-Color Sandwich Detector using InSb/PbSnTe," Infrared Physics, 1977, Vol. 17, pp 419-421.

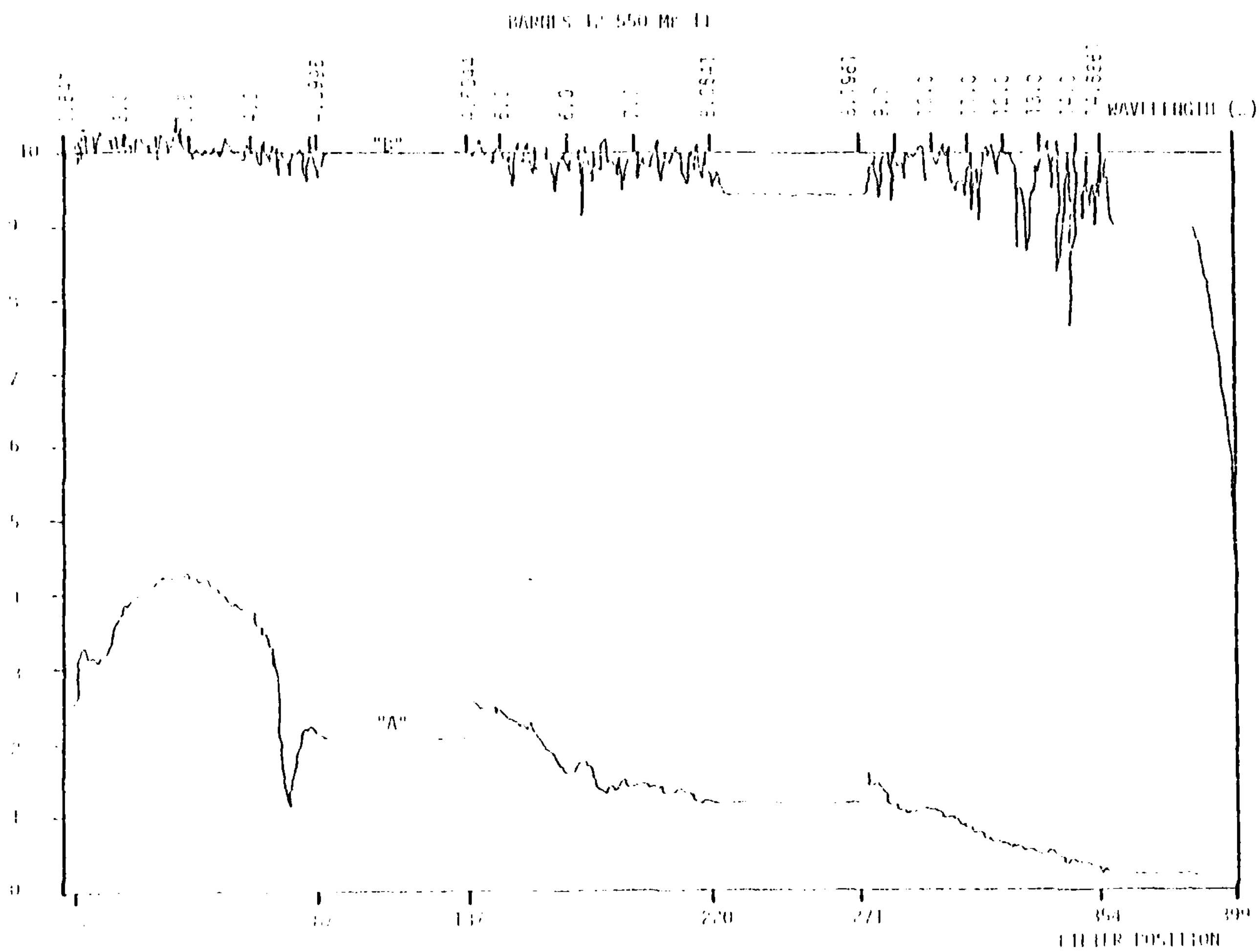

Figure 1. Spectral Scans: "A" = 1000 C Blackbody; "B" Trace "A" Normalized (Straight-line horizontal sections in the output trace are due to mechanical gaps between the sections of the continuously variable filter CVF in the optical head. There is no gap in the wavelengths covered).

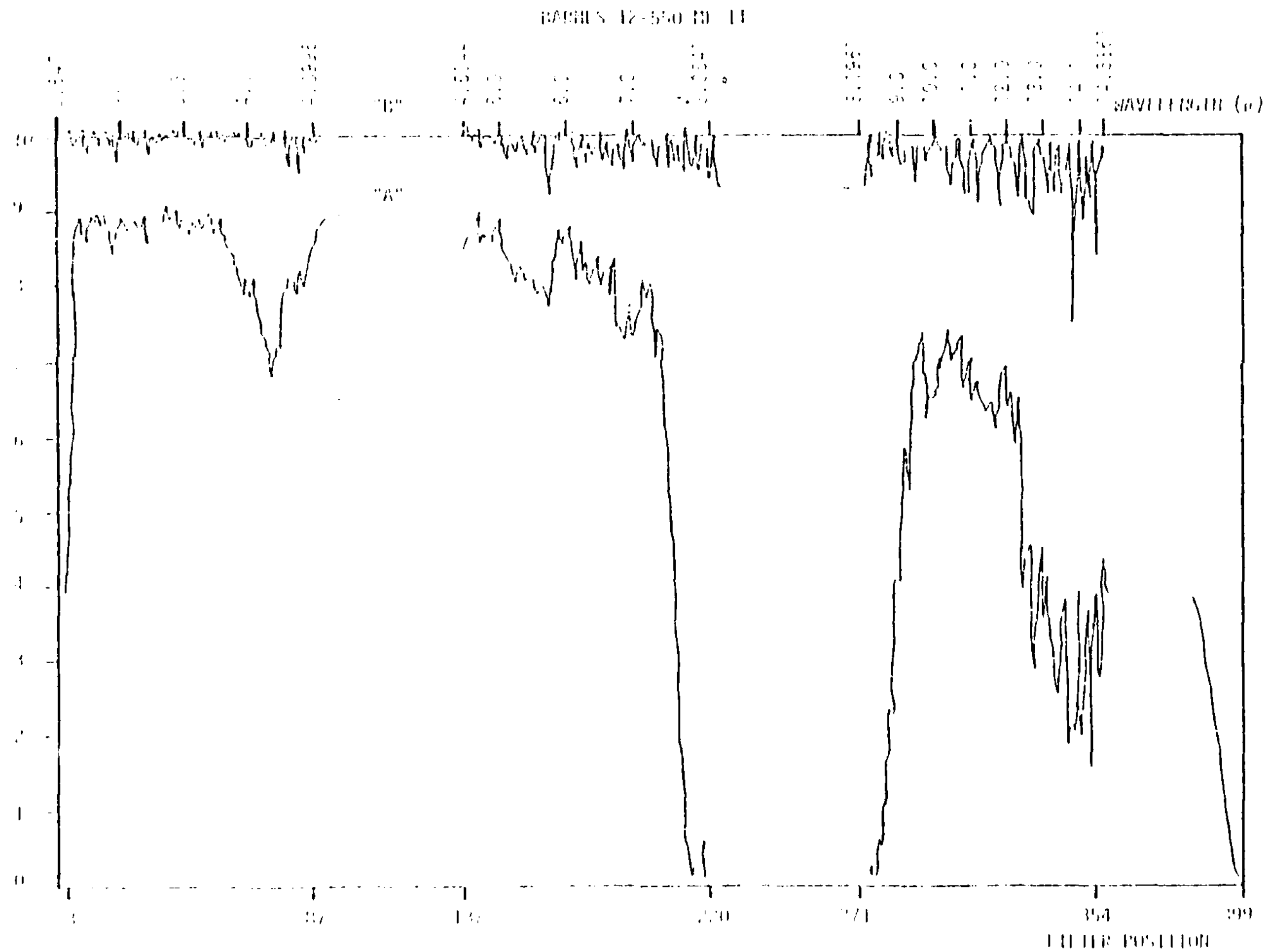

Figure 2. Spectral Scans: "A Gas Cell with 1-Mil Teflon Windows Filled with Nitrogen at 1 psi above Atmosphere; "B" Trace "A" Normalized.

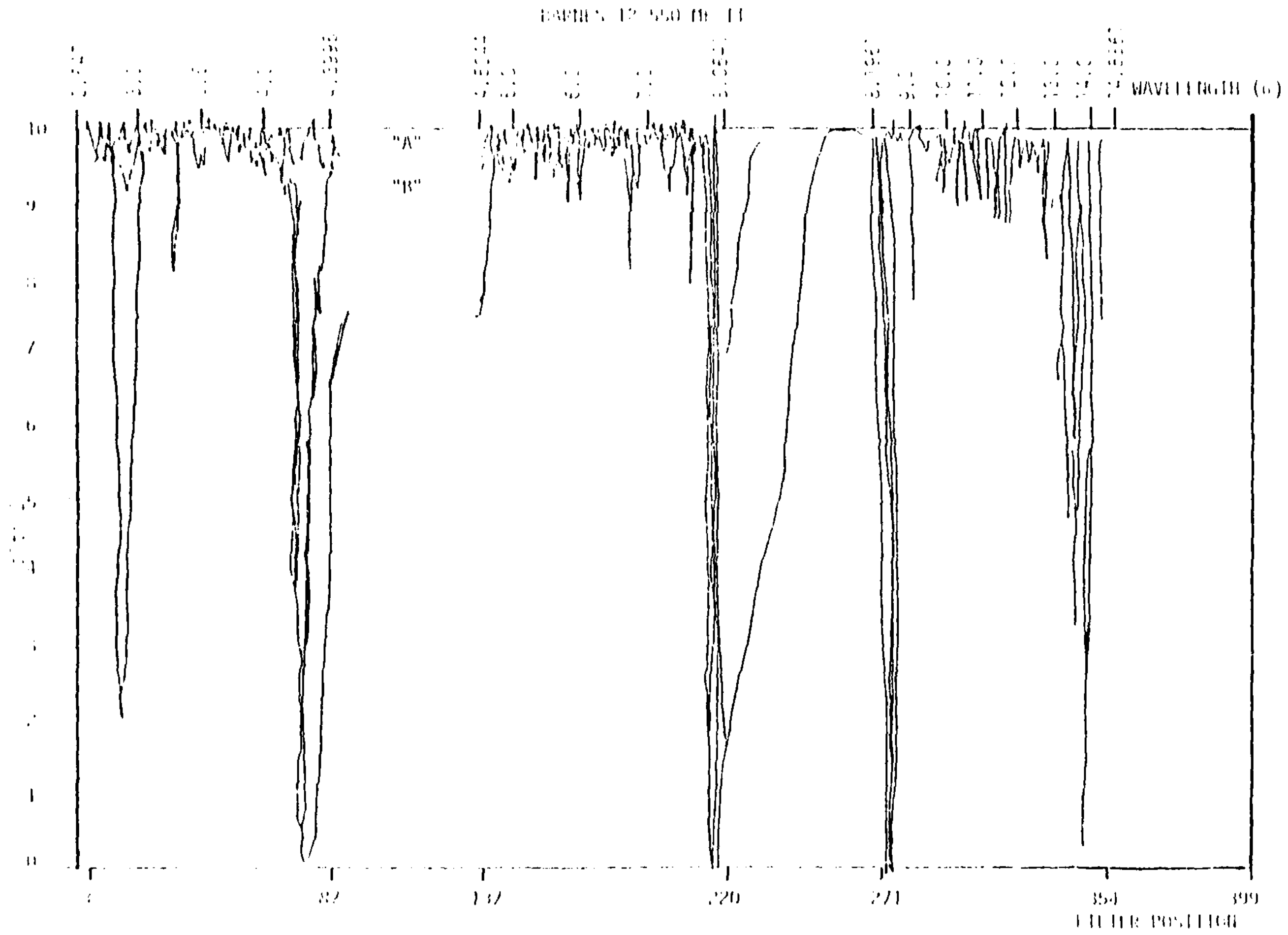

Figure 3. Spectral Scans: "A" Normalized Gas Cell; "B" Cell with 1.03% CO_2. Other traces show higher concentrations.

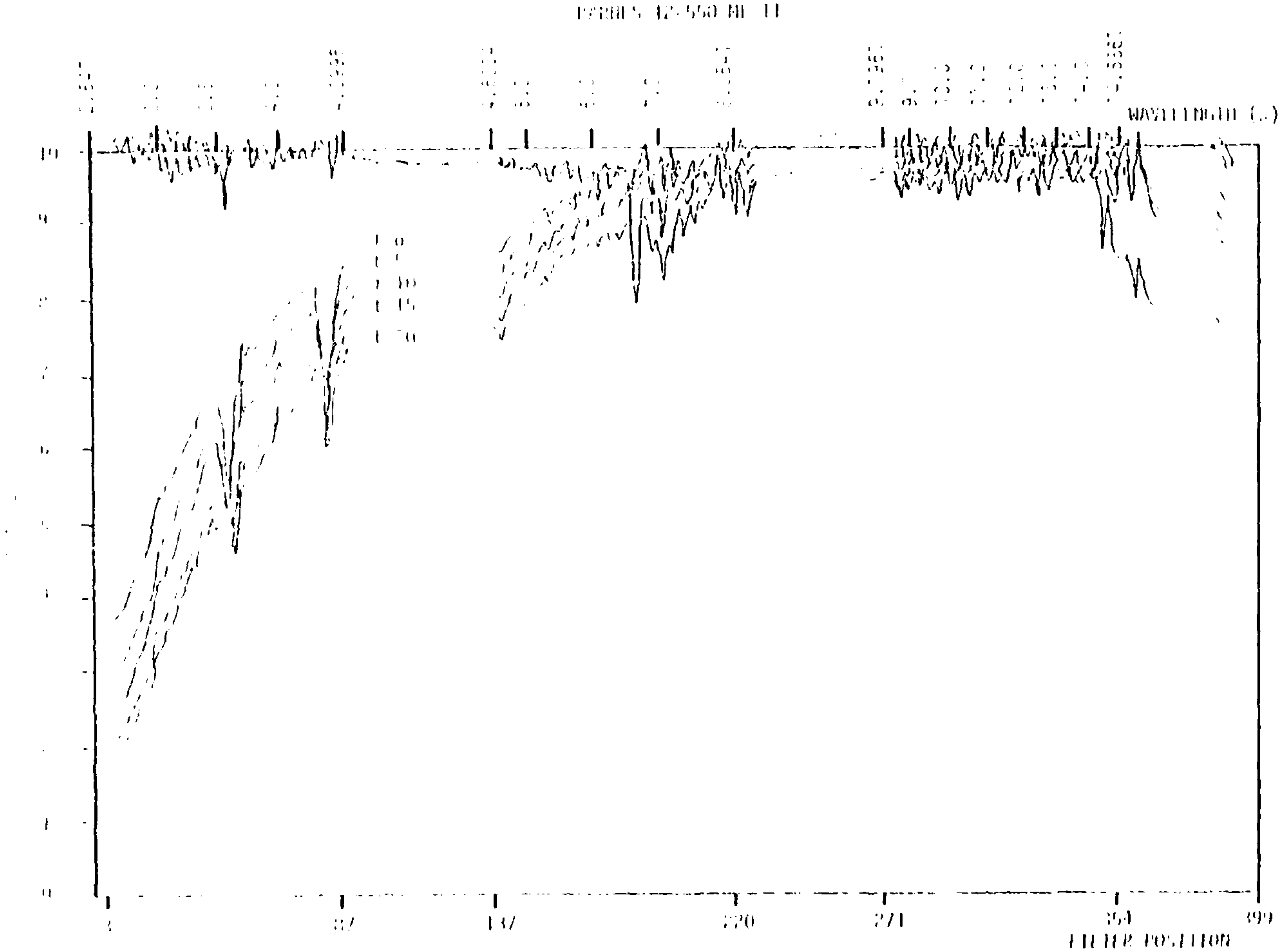

Figure 4. Spectral Scan of Fog Oil (concentration 0.5g/cm^3) at 5-minute intervals.

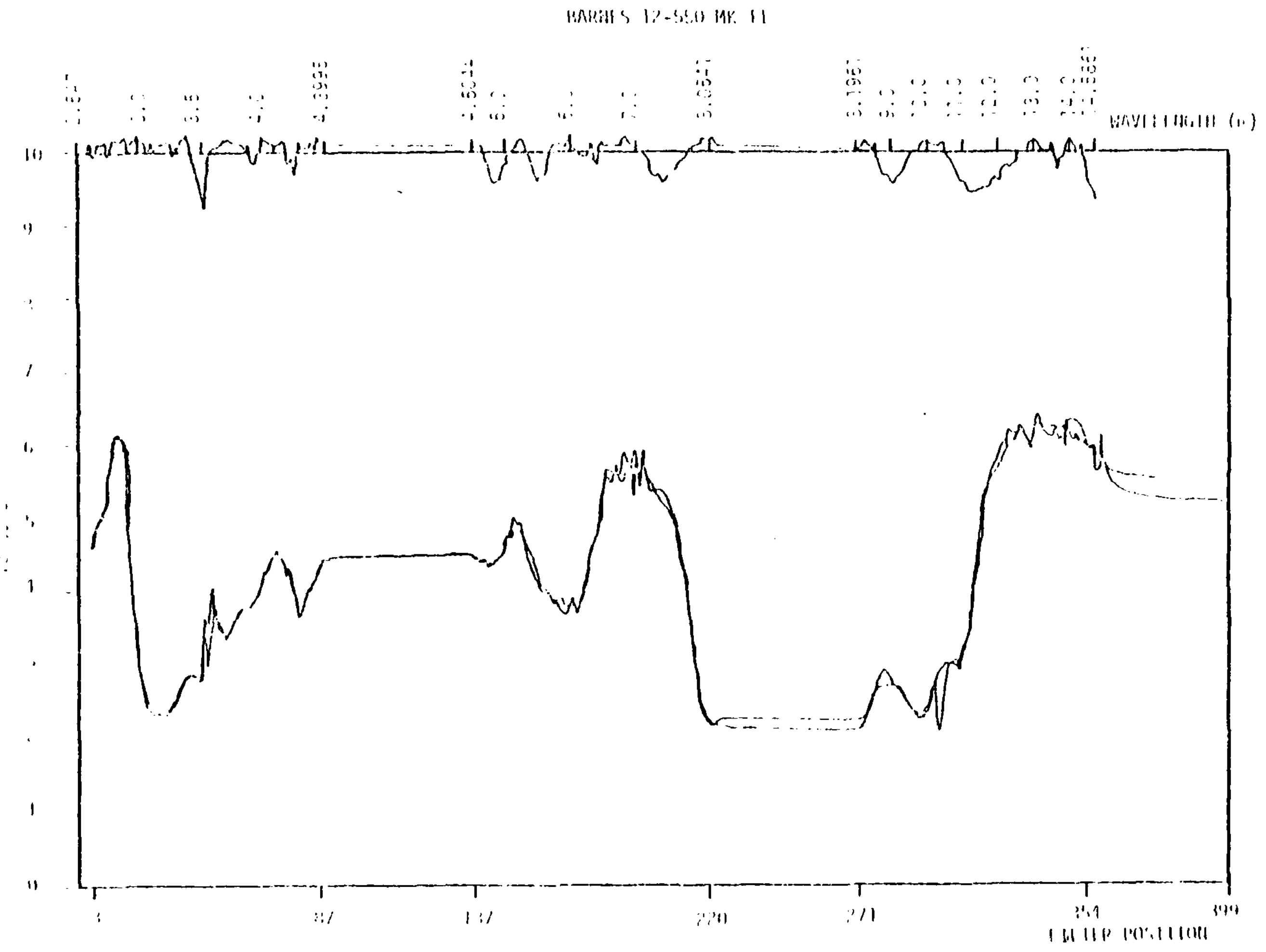

Figure 5. Spectral Scan of Red Phosphorous (concentration $0.7g/cm^3$).

AIRBORNE TRANSMISSOMETER CONSIDERATIONS

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There are several reasons for not using the optical scheme of the "projected beam" transmissometer in airborne infrared measurements. Probably the most significant one is that the data from this type transmissometer does not correlate well with the signals obtained by seekers used in corresponding atmospheres and ranges. It is believed that rescattering of detectable radiation by particles and droplets in or near the path of the optics increases the indication of a transmissometer but decreases the contrast signal in a seeker. Also, since transmissometers normally chop the emitted beam and do not respond to steady radiation, they are not sensitive to scattering of sunlight into the measuring path, as are seekers.

However, both of these effects would be appropriately measured by a passive detector having a small instantaneous field of view and a scanning angular coverage similar to that of a seeker. Such a detector and scanner is now commonly called a FLIR (Foward Looking Infrared).

An alternative approach for a transmissometer system would consist of visible (TV) and IR scanners (FLIRs) covering the .4 to 1.1 μm band, the 2 - 5μm band, and the 8 - 14 μm band, and contrast detection and tracking signal processing equipment. The method would simply be to lock the detection circuit onto the target signal so as to continuously read the position and size of the target contrast data in the data field. Any object of constant temperature or visible contrast will do as the target. Data processing would consist of extracting the <u>ensemble average</u> of the contrast between the target and its background. The tracking logic would determine and present to the recorder the address of the target as well as its size. Range must also be recorded along with factors describing the atmosphere.*

In application, flying toward the target as range zero is approached, the detected signal would approach its maximum value. Therefore the system is self-calibrating. The data obtained would be compared with the normal contrast extinction function, $C_R/C_I = \exp(-K \cdot \sigma \cdot R)$ at several ranges. Figure 1 shows the expected character and range of the data for atmospheres between light haze and fog and for the path lengths and ranges of greatest interest.

For the transmissometer function, the TV camera should use a silicon diode array vidicon which has a unity gamma. A motorized iris would be preset to provide linear exposure at range zero and would be constant during a run.

*For example, LOWTRAN requires dry bulb temperature, dew point temperature and sea level visible range or some measure of the atmospheric aerosol.

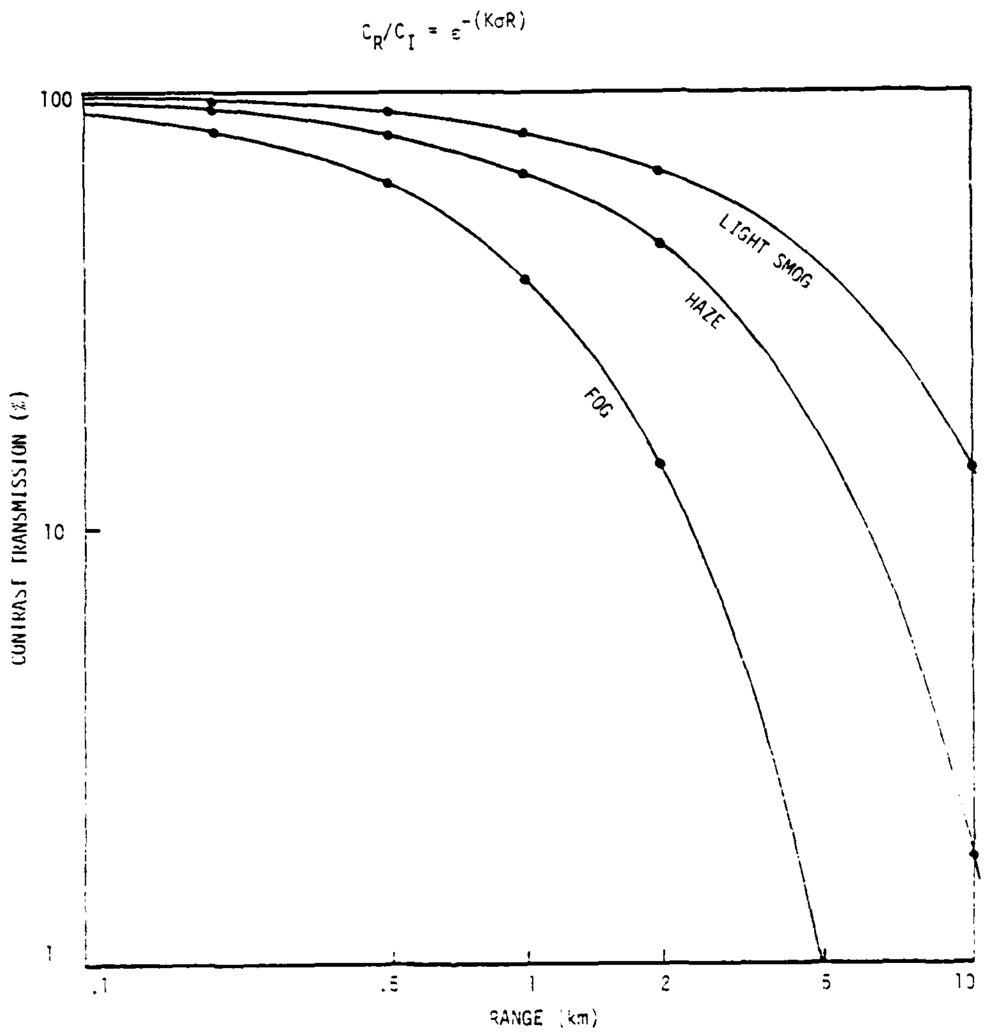

Figure 1. Contrast Transmission for Three Typical Atmospheric Conditions.

MARINE TRANSMISSION MEASUREMENTS

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The Navy has been actively engaged in laser extinction measurement programs since the early 1970's. The specific interest is in marine paths of moderate length ($\sim$5 km) for (DF, HeNe, ND-YAG, CO, CO_2) laser sources in the 1800-6600 cm^{-1} (and generally 0-7800 cm^{-1}) band. Typical measurements are taken with full meteorological support and seek a variety of atmospheric (water vapor) pressure conditions.

Among the principle objectives of Navy marine measurements is the definition of an accurate, reliable data base for the validation of present and future laser transmission models. As a consequence, it is hoped that significant improvement in transmission modeling can be realized with this field data augmented by laboratory measurements.

An immediate payoff from measurement programs is the collection of high quality, high resolution (FTS) transmission spectra for a variety of atmospheric paths which can be used in comparison with existing models (HITRAN, LOWTRAN).

Notable problems encountered in taking actual transmission measurements include atmospheric turbulence and the effects of water vapor absorption An accurate characterization of this latter process will, hopefully, be a significant result of the measurement program.

The accompanying figures show measurement and model comparisons.

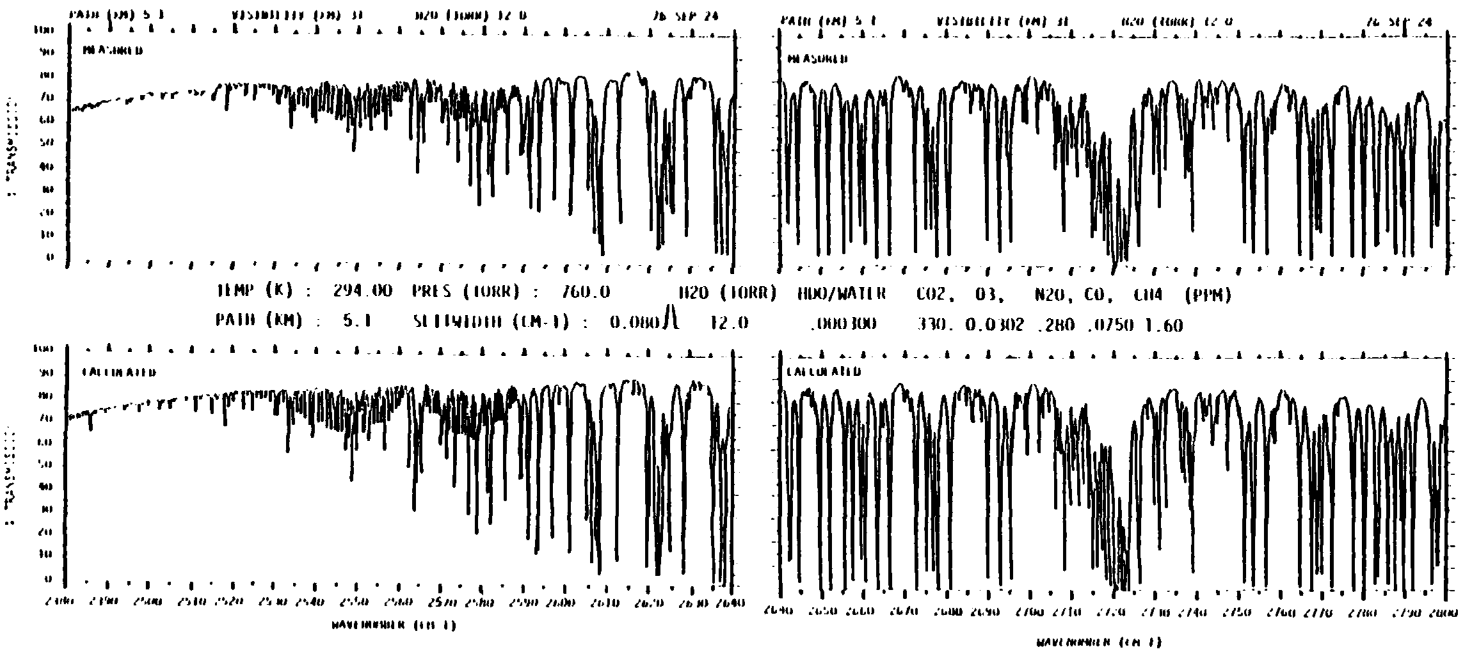

Figure 1. Comparison of Measured and Calculated Atmospheric Transmission Spectra in the 2480 to 2800 CM^{-1} Spectral Region. Upper Trace-Measured Transmission for 12 TORR H_2O, 5.1 km Pathlength and 31 km Visual Range (2% Contrast at .65 μm); Lower Trace-Calculated Molecular Absorption For Conditions Indicated Above the Trace.

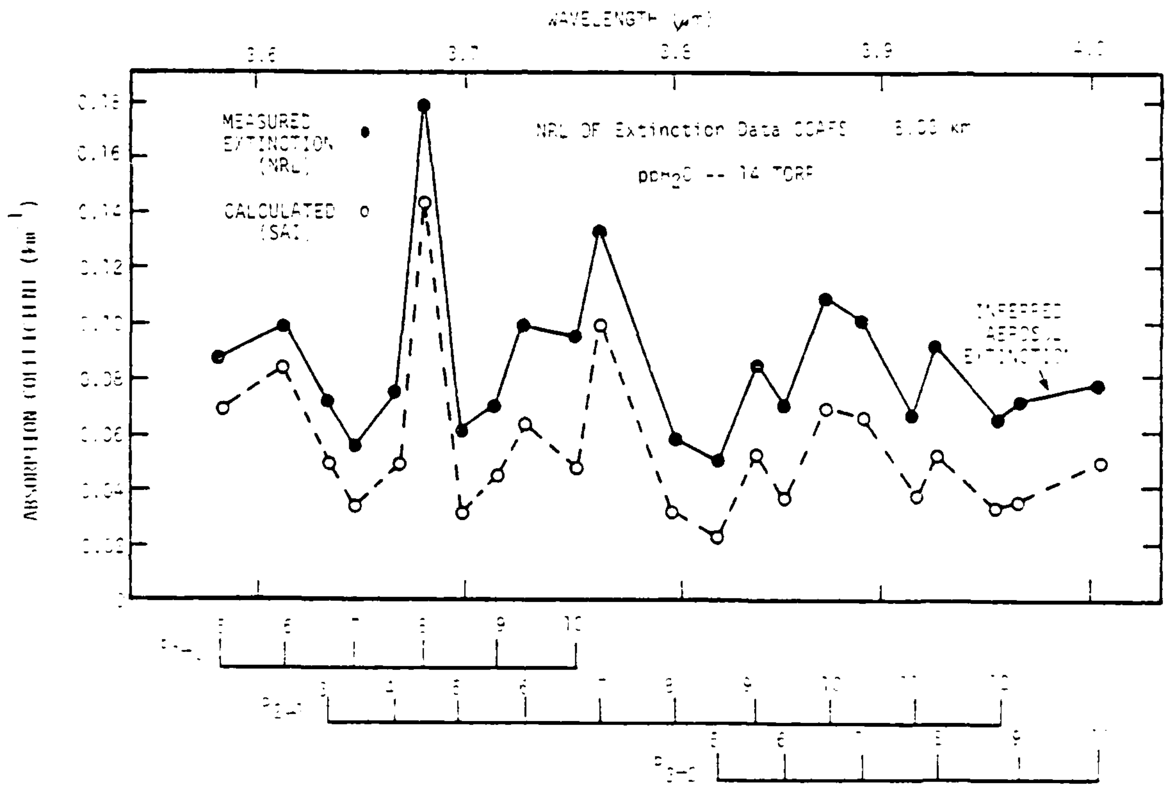

Figure 2. Comparison of Calculated Molecular Absorption (o) with Field Measurements (●) of DF Laser Extinction.

OPAQUE DATA COLLECTION AND ANALYSIS PROGRAM

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Hanscom Air Force Base, Massachusetts

The OPAQUE (Optical Atmospheric Quantities in Europe) program grew out of a proposal by a NATO study group to develop a statistical data base for atmospheric optical properties in the European environment. It is directed towards a realistic assessment of NATO force capabilities with regard to existing and potential electro-optical (EO) systems. The data base will be used in conjunction with validated transmission models to evaluate various EO systems, but the general measurement program is not tied to any particular choices of such systems.

Seven sites have been selected (Figure 1) as representative of the European environment. At these sites, measurements have been (and are being) taken every hour on the hour (LMT) for a two year period. The United States has collected data during the winter of 1976-77 and summer of 1979. The European programs were initiated in 1979 and will continue through 1980.

Presently, over 90 months of data from the various stations have been collected with final submission due by 1981.

The measured optical and meteorological parameters are outlined in Figure 2.

In summary, the ultimate AF/DOE payoff will be statistics of EO/IR weather in the European environment: two years of seasonal ground station data as well as airborne measurements.

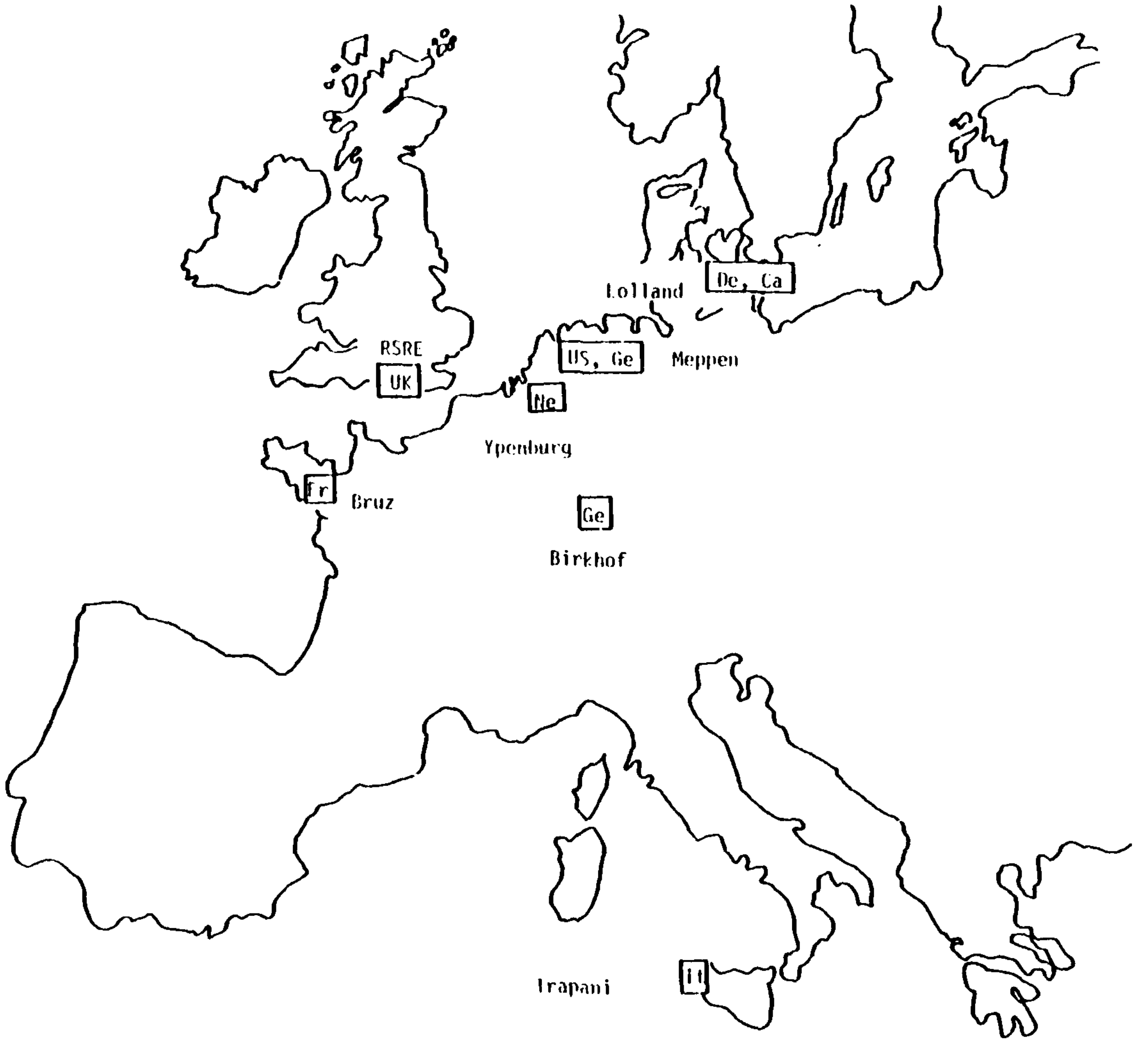

Figure 1. NATO Program on Optical Atmospheric Quantities in Europe (OPAQUE).

OPAQUE MEASURED OPTICAL QUANTITIES

VISIBLE

- Transmission, Day-Night, Photopic, $500\ m < V_n < 20\ km$
- *Scattering Coefficient, Day-Night, Several λ's
- Horizontal and Vertical Illuminance, Day-Night
- Path Luminance, Day-Night, $L(\theta, \theta_0)$, $L(\cdot)$
- Spectral Solar Transmission, $T_i(\lambda)$
- *Direct Contrast Reduction
- *Angular Scattering Function
- *USAF and FRG Aircraft Measurements

INFRARED

- Transmission (650°C Source), 500 m,
- *Laser Transmission,
- *Laser Scattering, 1.06, 10.6 μm,
- *Sky & Background Radiance.

MEASURED METEOROLOGICAL QUANTITIES

SIMULTANEOUS WITH OPTICAL MEASUREMENTS:
- Temperature
- Dew Point or Relative Humidity
- Rain Rate
- Pressure
- Wind Speed and Direction
- *Cloud Height and Cloud Cover
- Aerosols

Standard Meteorological Observations from Nearby Meteorological Stations. Including Radiosonde Flights.

*Not all stations

Figure 2. Measured Optical and Meteorological Parameters.

MODIFICATIONS TO THE BARNES ENGINEERING COMPANY MODEL 14-WP TRANSMISSOMETER FOR LONG PATH MEASUREMENTS AT THE [illegible]

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Air Force Wright Aeronautical Laboratories/Avionics Laboratory
Wright-Patterson Air Force Base, Ohio

[illegible] is engaged in an in-house research program to measure broad band atmospheric transmission over an eight kilometer land path at the Targeting Systems Characterization Facility (TSCF), Wright-Patterson Air Force Base, Ohio. The Barnes Model 14-WP Transmissometer has not (to our knowledge) previously been used for long path transmission measurements. Our experience at the TSCF suggest that the Model 14-WP configuration may not permit measurement accuracies of ± 1% over an eight kilometer land path. Martin (1979) demonstrated that modifications to the Barnes Model 14-WP transmissometer electronic detecting circuitry and the receiver and source optics are necessary to achieve high measurement accuracy in the presence of optical turbulence over long atmospheric paths.

The redesign and fabrication of a new receiver optics assembly was required because of the atmospheric turbulence effects encountered when propagating the source beam over the eight kilometer range. The Barnes Model 14-WP standard receiver optics creates a blur circle larger than the detector surface (Martin, 1979). In the presence of atmospheric turbulence, the blur circle may temporarily drift off the detector surfaces due to beam wander and modulate the output. Since scintillation of the beam intensity due to turbulence occurs simultaneously, the interpretation of the measurements to calculate atmospheric transmission loss is subject to large error. The new receiver optics designed by the Avionics Laboratory results in a much smaller blur circle and its size can be controlled. The object of the design is to ensure that all the energy entering the entrance aperture of the receiver optics is focused and contained on the detector.

Even with changes in the receiver optics, it was still necessary to change the Barnes electronic receiver circuitry. Because of atmospheric turbulence, the dominant noise in the receiver output signal is the intensity scintillation which results from the propagation through the turbulent medium. For path lengths of eight kilometers or more the Barnes electronics would not work properly at the signal to noise levels encountered, and it was [illegible] Also, the Barnes electronics were temperature dependent which biased [illegible]

[illegible] measurements. The design placed the black-body cavity, approximately one inch in diameter, more than five inches from the aperture at the focus of the f/3 primary mirror. A gradual falloff in the intensity of the collimated

beam from the primary mirror was observed as the beam was scanned from the center to the edge of the mirror. Because the receiver optics are smaller in diameter than the source primary, calibration procedures were questionable. This will be remedied by placing the black-body cavity closer to the aperture. However, this placement of the black-body does not permit simultaneous operation of the visible and black-body sources.

REFERENCE

Martin, William C., "Optical Tests on a Barnes Transmissometer", these proceedings, page 51.

OPTICAL TESTS ON A BARNES TRANSMISSOMETER

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The Electro-Optical Sensor Science and Engineering Group recently purchased two complete transmissometer systems (Model 14-WP) from Barnes Engineering Company for the purpose of measuring atmospheric transmission in the visible and near infrared (IR) spectral regions. These measurements were to be made over horizontal path lengths of up to eight kilometers.

Repeated attempts to measure transmission with an accuracy of ± 1% over an eight kilometer path were unsuccessful. Since this transmissometer, to our knowledge, has never been used over these longer path lengths it was deemed necessary to perform a complete analysis of the instrument and precisely determine its optical characteristics. The results of this analysis are the subject of this presentation.

SYSTEM DESCRIPTION

The transmissometer source consists of a 49.5-inch focal length primary mirror with a 16.5-inch clear aperture, a small diagonal fold flat, the aperture wheel, chopper mechanism and light sources (visible and blackbody). The transmissometer source is intended to function like a searchlight, with the illuminated apertures located in the infinity focal plane of the primary, sending out a collimated beam with a divergence dependent upon the aperture size being used and the focal length of the primary mirror. Figure 1 shows an optical layout of the source assembly.

With each source there are three receivers which have Si, InSb and HgCdTe detectors to cover the visible, 3-5 micrometer (μm) and 8-12 μm spectral regions, respectively. The pertinent parameters of each of the receivers is given in Table 1 below. The optical configuration of a receiver is shown in Figure 2.

The receiver fore-optics (primary and secondary mirrors) image the source aperture in the plane of the field stop; this image is relayed at one-to-one by the transfer mirror assembly to a second image point, which in turn is again relayed at unit magnification through the Continuously Variable Filter (CVF) to the detector. The fore-optics in both the visible and 3-5μm receivers are described by Barnes as spheres, whereas the primary mirror of the 8-12μm receiver is an asphere. Focusing of each receiver for minimum spot size is accomplished by moving the secondary.

CONCLUSIONS AND COMMENTS

The results of AFWAL/AA tests suggest that attempts to measure atmospheric transmission over long paths of eight kilometers or greater with accuracies of ± 1% may exceed the design limitations of the Barnes Model 14-WP transmissometer with the CVF provided. The data indicates that the transmissometer sources, from an optical viewpoint, should present no problems in terms of obtaining accurate transmission measurements. Nevertheless, the receivers may not be adequate for longer path measurements. While it is certainly true that the receivers are not intended as imaging devices, it is necessary that all the energy from the source, as collected by the receiver, fall on the detector--none of it must be allowed to fall outside the detector--or a loss of accuracy will result. In other words, a flat field-of-view over a reasonable pointing angle is required of each receiver. This can only be achieved in the current units by either having larger detectors or smaller blur circles. The former is unattractive from signal-to-noise considerations. Reworking the existing optics to improve spot size is feasible. However, we have experimentally determined that the 4.25-inch collection aperture of the Barnes receivers (plus obscuration) is too small for use at 8km--the signal-to-noise for certain CVF settings is practically zero. This would indicate the need for a larger receiver collection aperture. Details of this analysis can be found in AFWAL/AA-TR-79-1123.

One question which needs to be addressed is why Barnes found it necessary to aspherize the primary mirror of source #2. The effects of the two different primary mirror shapes on beam distribution at an 8km propagation distance are largely unknown. They should be minimal, but an actual experimental determination has not yet been made. This will be delayed until adequate means for collecting the source energy are developed.

At this time an effort is underway by the Air Force to completely redesign the receiver optical system. It is felt that if an adequately small blur circle can be obtained with the new optics, then the theoretically obtainable accuracy of the entire system will no longer be optics limited.

REFERENCE

Martin, William C., "Optical Tests on a Barnes Transmissometer System," Technical Report AFWAL/AA-TR-79-1123, February 1979.

TABLE 1

TRANSMISSOMETER SYSTEM PARAMETERS

	DETECTOR		
	Si	InSb	HgCdTe
Focal Length	8.5"	8.5"	8.5"
Aperture	4.25"	4.25"	4.25"
Detector Size	1mm x 1mm	.030" dia	.5mm x .5mm
Detector Window	--	Si coated	Irtran 2
Field-of-View	5 mrad	2.5 mrad	2.5 mrad

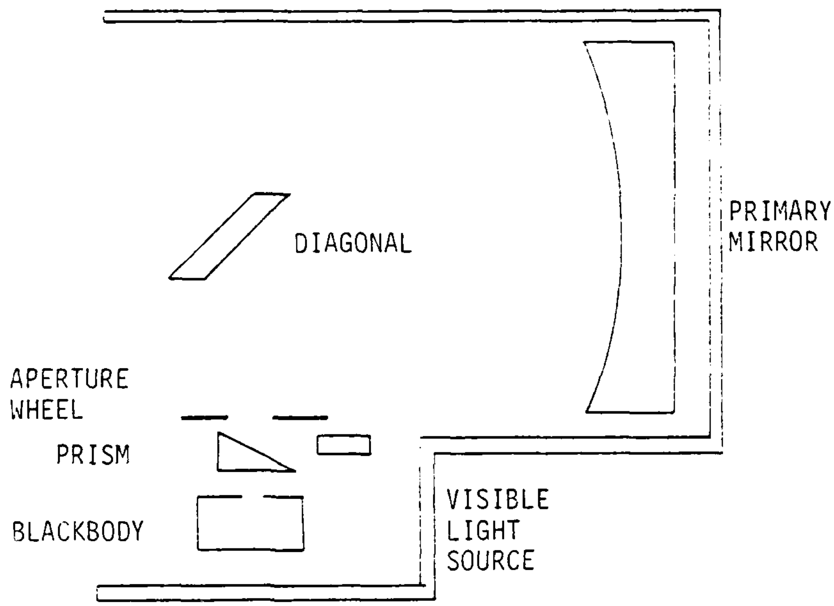

Figure 1. Source Optical Layout.

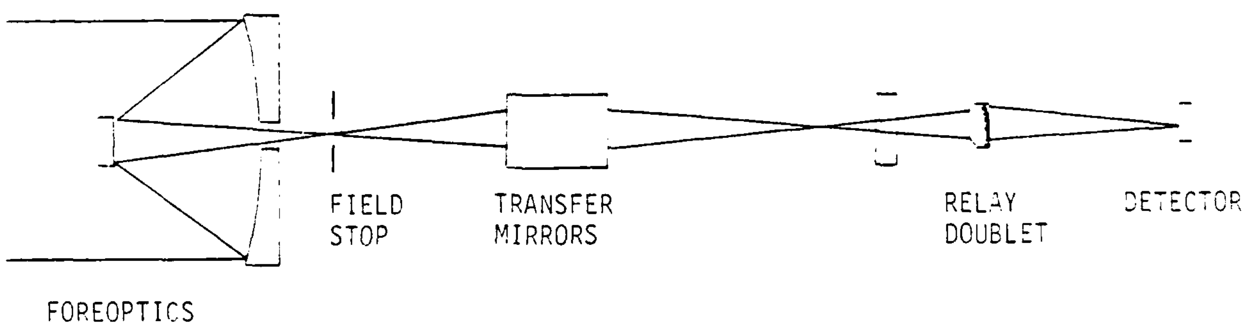

Figure 2 Receiver Optical Layout.

DIRT I, II

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Atmospheric Sciences Laboratory
White Sands Missile Range

DIRT (Dusty Infrared Tests) I, II had as their objectives real time, realistic battlefield measurements and data collection of transmission and particle size. Detonation of typical Army projectiles dispersed particulates within line of sight. Attenuation and transmission were continuously monitored with devices such as the NRL filter transmissometer.

Mobile meteorological support included the standard measurements: temperature, pressure, relative humidity, wind direction and speed as well as solar radiation (incoming and outgoing).

In addition to the meteorological parameters, impact criteria (crater diameter and depth) were recorded for future data analysis.

The accompanying figures provide examples of measured data and reveal temporal effects of battlefield obscurants on transmission.

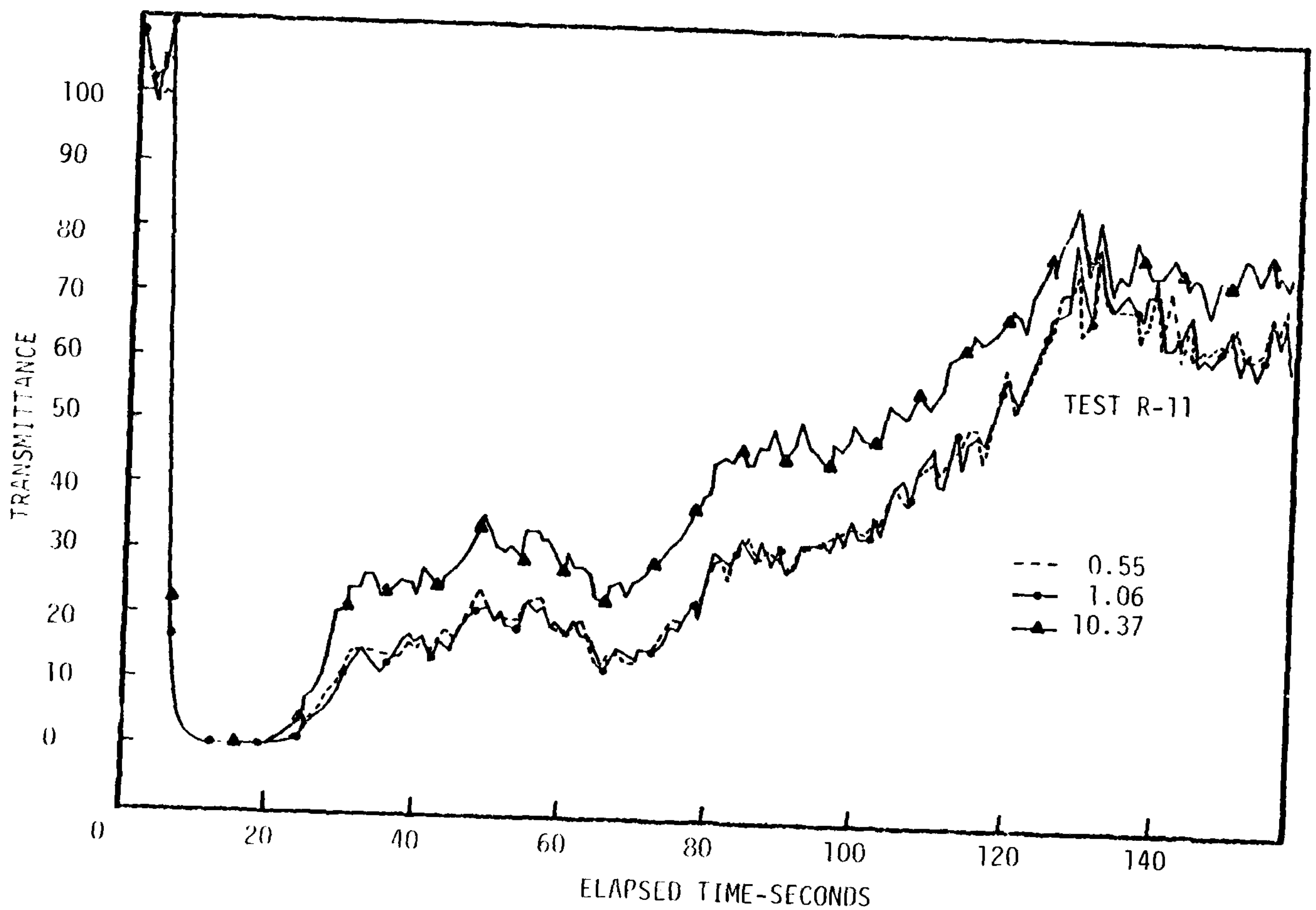

Figure 1. DIRT-11 Optical Data.

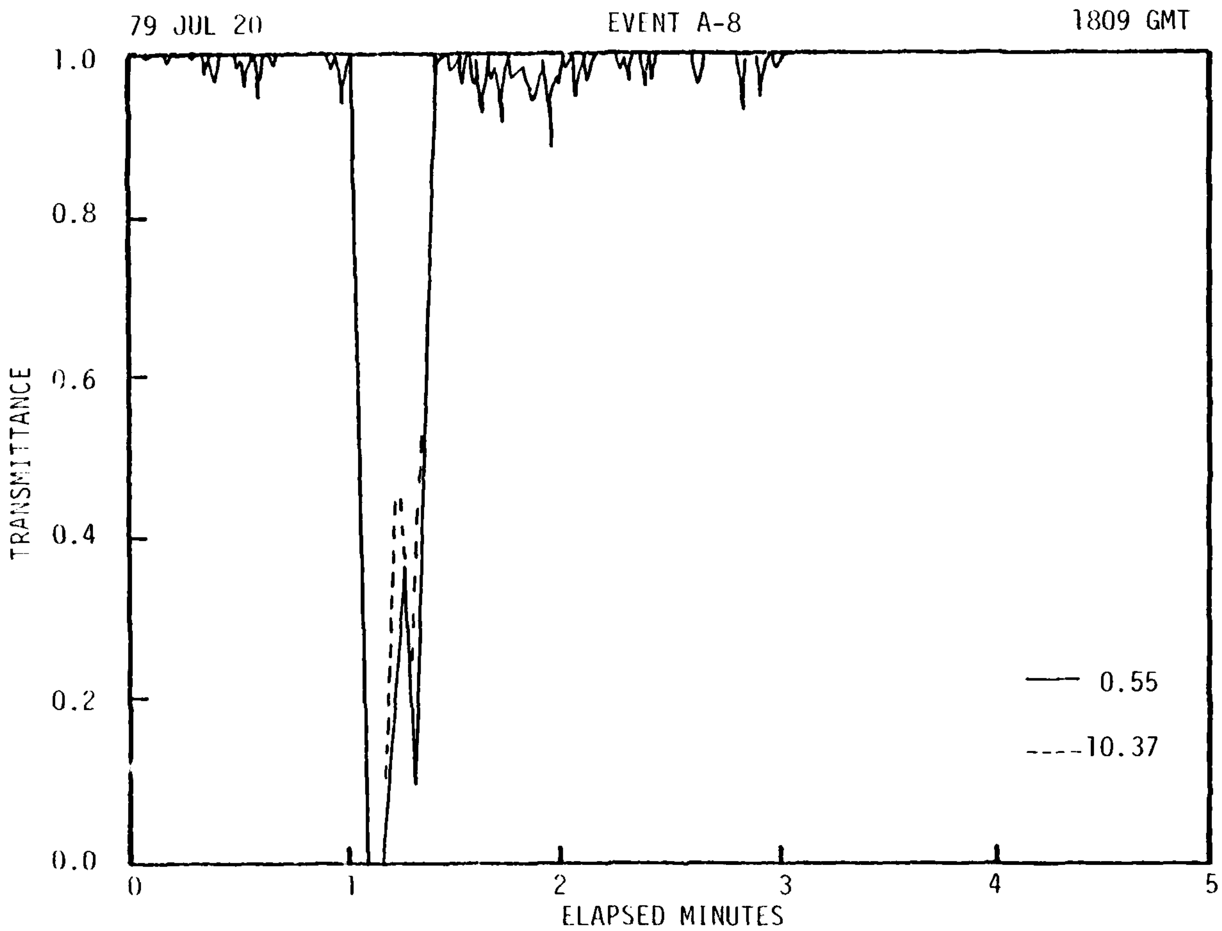

Figure 2. NRL Filter Transmissometer Data, Buried 155mm Projectile.

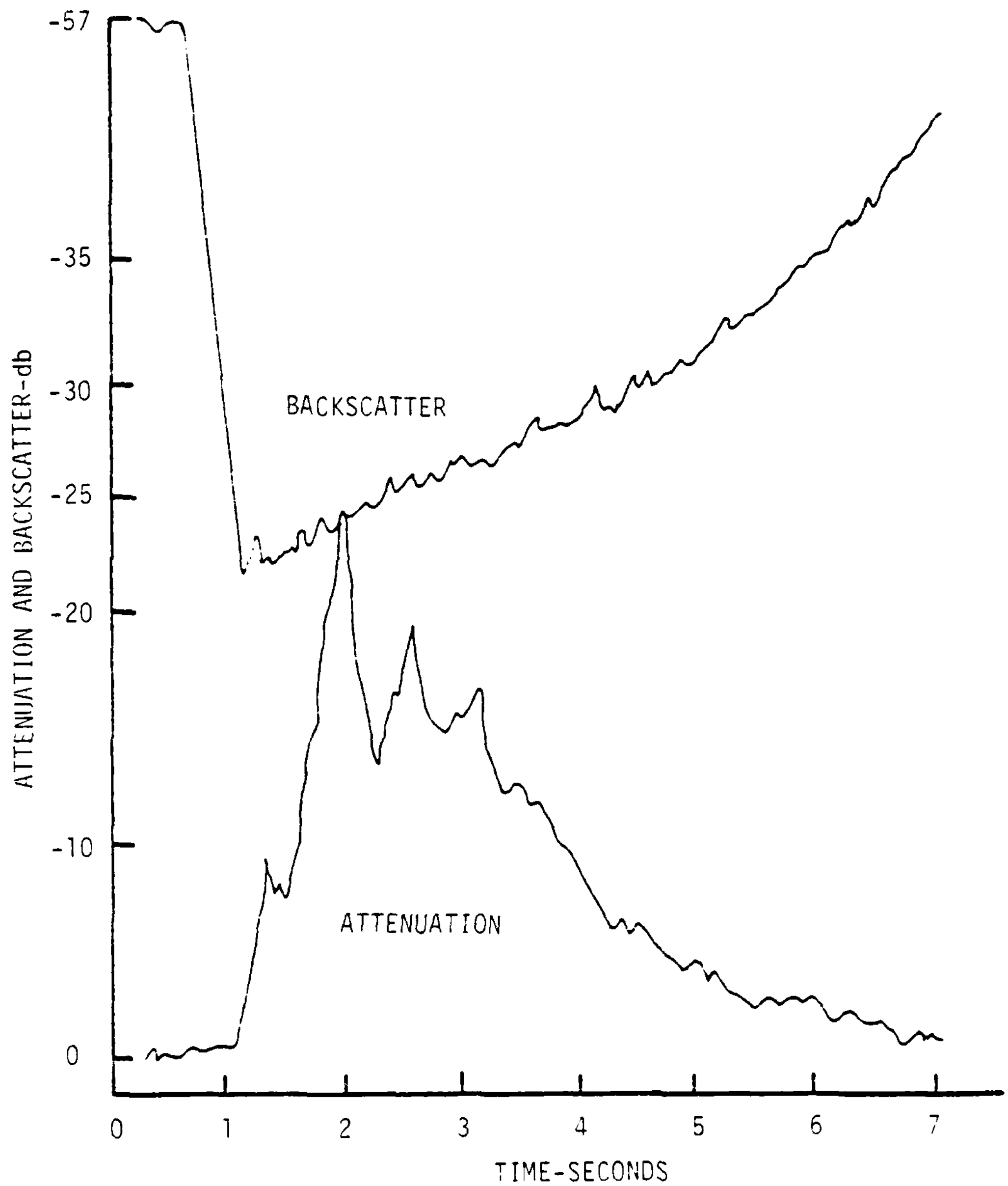

Figure 3. DIRT-II: NV and EOL 95 GHz Radar 155mm HE Detonation.

DOCUMENTATION OF ATMOSPHERIC OPTICAL PROPERTIES DURING THE TESTING OF AN ULTRAVIOLET VOICE COMMUNICATION SYSTEM

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During the last week of July and the first week of August 1979, a research oriented ultraviolet voice communication system was tested in a desert like atmosphere. In order to verify the effects of atmospheric propagation and scattering on the performance of this ultraviolet voice communication system, a series of measurements was made to determine atmospheric optical properties. The atmospheric measurements made included ozone concentrations, aerosol particle size distributions, single scattering phase functions, temperatures, humidities, color photographs, extinction coefficients and scattered radiance. Extinction coefficients and scattered radiance were measured at distances ranging from 0.7 to 3.0 kilometers. These measurements were made using a relatively isotropic 200 watt mercury-xenon lamp. The angular dependence of radiation coming from this lamp was measured and taken into account in the modeling. The spectral distribution of radiation coming from the lamp in the wavelength bandpass of the ultraviolet radiometer is shown in Figure 1. Extinction measurements were made by pointing the detector directly at the 200 watt lamp with a narrow field-of-view. Scattered radiance measurements were made by systematically rotating the detector optical axis away from the source-to-detector line-of-site to various elevation angles. As the elevation angle of the detector optical axis was increased above the source-to-receiver line-of-site, the detector field-of-view was also increased to allow for a larger scattering volume. Mie scattering theory was used together with the measured particle size distribution to predict aerosol scattering and aerosol absorption coefficients such as those shown in Figure 2. Ozone concentration measurements were used to predict ozone absorption coefficients also shown in Figure 2. Ambient temperature and pressure were used together with Rayleigh scattering theory to predict the scattering due to molecular species. The sum of all of the exponential coefficients is equal to the extinction coefficient also shown in Figure 2. Measured values of the extinction coefficients are shown in these figures as circular data points.

An atmospheric propagation and scattering model known as OSIC (Off-Axis Scattered Intensity Calculation) was used to predict the scattered radiance at various elevation angles and distances from the source lamp. Comparisons of measured and predicted scattered radiance are shown in Figure 3 for measurements made on July 26.

Once the validity of the OSIC model had been established for predicting both directly transmitted and scattered radiation, it was used to successfully predict the performance of the ultraviolet voice communication system.

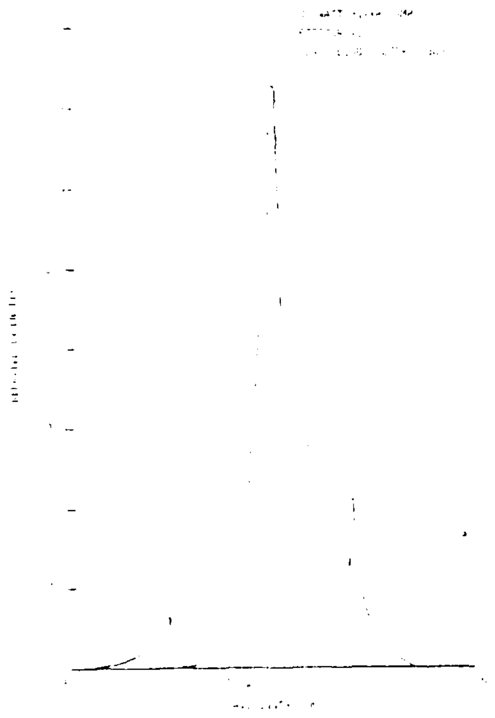

Figure 1. Spectral Distribution of Radiation from Mercury-Xenon Lamp in Wavelength Bandpass of Ultraviolet Radiometer.

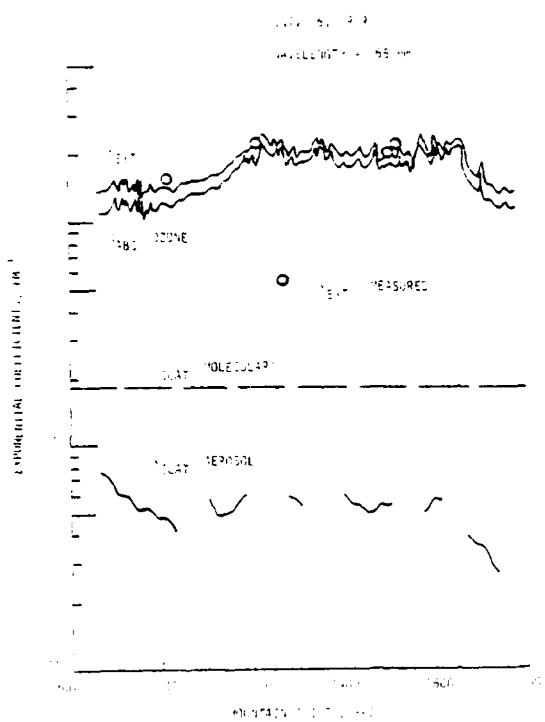

Figure 2. Absorption Coefficients from Measured (Ozone) Concentration.

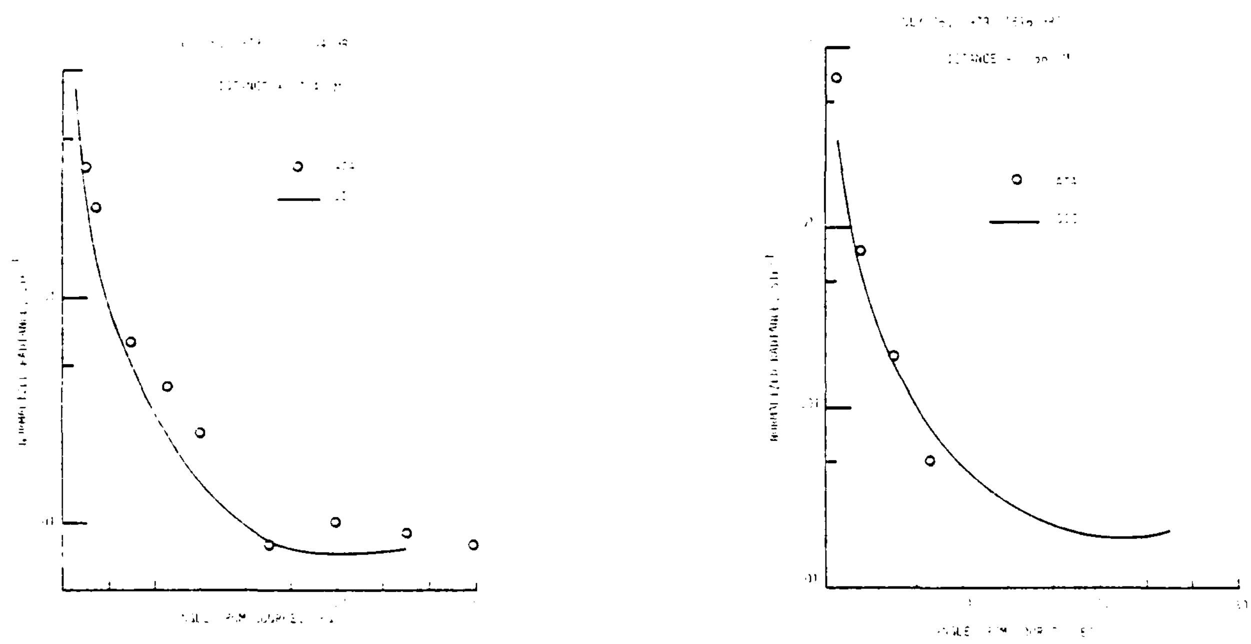

Figure 3. Measured and Computed (OSIC) Scattered Radiance.

TRANSMISSION MEASUREMENTS AND SIMULATION

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Ann Arbor, Michigan

Modeling of atmospheric transmission in the visible and IR bands is of major importance to any EO system evaluation program. Although much progress has been made on various codes, the high variabilities of atmospheric properties and operational scenarios continue to present formidable modeling problems.

Transmission measurement programs are critical for model validation and in fact, the measurement of atmospheric properties is necessary to drive the models. Consequently, there is a definite need for communication between the modeling and measurement communities.

Figure 1 gives the basic definitions of aerosol transmittance, calculations and simulation. Figures 2 and 3 provide comparison between measured and computed transmission.

From a modeler's viewpoint, several suggestions for possible improvement in the acquisition of broadband transmittance measurements can be offered.

1. In the 3-5 μm band, use two filters to cover the two distinct windows: 3.3-4.2 μm and 4.4-5 μm.

2. Use a filter and detector combination to tailor the transmissometer system response towards similarity to the (military) system of interest (e.g. for the 3-5 μm region, an InSb detector with a range filter could be used to duplicate a FLIR response.)

3. Make spectral measurements.

BASIC DEFINITIONS

$T(\lambda) = \exp[-K(\lambda)L]$,

$T \equiv$ transmittance,

$K \equiv$ attenuation coefficient (km^{-1}),

$L \equiv$ path length (km), and

$K(\lambda) = K_{ML}(\lambda) + K_{MC}(\lambda) + K_{AS}(\lambda) + K_{AA}(\lambda)$.

Subscripts Identify Attenuation Mechanisms

ML $\equiv$ molecular line absorption,

MC $\equiv$ molecular continua absorption,

AS $\equiv$ aerosol scattering, and

AA $\equiv$ aerosol absorption.

Average Aerosol Transmittance inferred by the measurement

$$\bar{\tau}_{AI} = \frac{\int_{\lambda_1}^{\lambda_2} \tau_A(\lambda)\,\tau_M(\lambda)\,R(\lambda)\,d\lambda}{\int_{\lambda_1}^{\lambda_2} \tau_M(\lambda)\,R(\lambda)\,d\lambda}$$

($R(\lambda)$ is the Instrument Response Function)

The standard Average Aerosol Transmittance

$$\bar{\tau}_A = \frac{\int_{\lambda_1}^{\lambda_2} \tau_A(\lambda)\,d\lambda}{\lambda_2 - \lambda_1}$$

We can define

$$\bar{K}_{AI} \equiv -\frac{1}{L} \ln \bar{\tau}_{AI}$$

and

$$\bar{K}_A \equiv -\frac{1}{L(\lambda_2 - \lambda_1)} \int_{\lambda_1}^{\lambda_2} \ln \tau_A(\lambda)\,d\lambda$$

and the question we consider is

$$\bar{\tau}_{AI} \overset{?}{=} \bar{\tau}_A$$

Figure 1. Equations Simulating Aerosol Transmissometer Measurements.

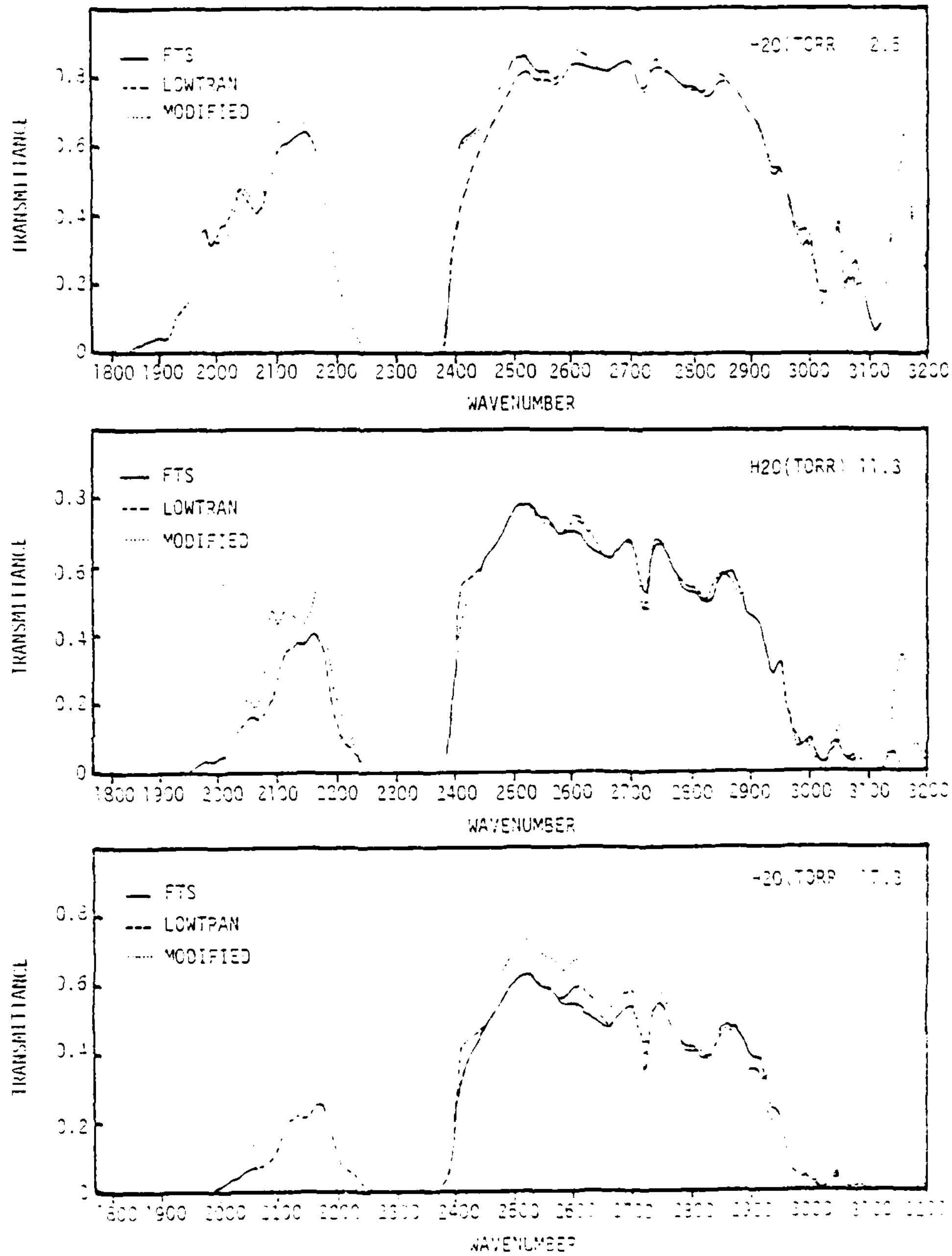
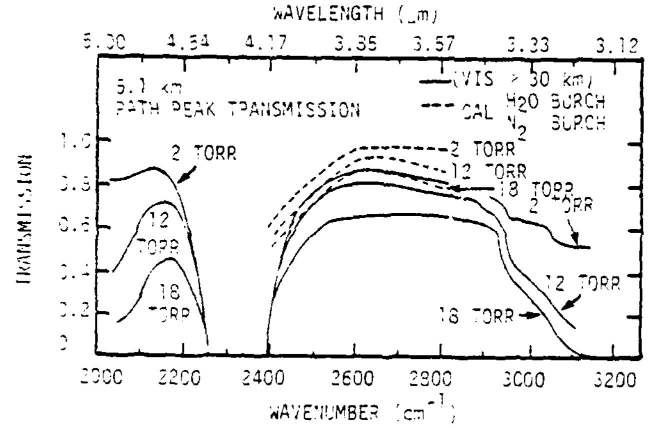
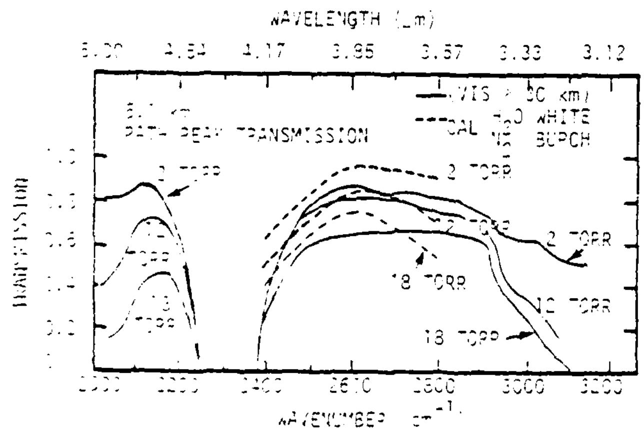


Figure 2. Comparison of NRL Fourier Transform Spectrometer (FTS) for a 5 km path with LOWTRAN Predictions. Note discrepancy between 2000 and 2250 cm^{-1} (4.0 - 4.4 μm).



a Using the H_2O Continuum Model of Burch



Using the H_2O Continuum Model of Watkins and White

Figure . Comparison of NRL Field Measurement Data to H_2O Continuum Calculations Based on Various Experimenters' Laboratory Measurements.

BARNES INTERCOMPARISONS TRIAL: PERSHORE

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Hanscom Air Force Base, Massachusetts

Intercomparisons of the Barnes transmissometer systems utilized by nations participating in OPAQUE were performed on determine, among other things, the accuracy limitations of the IR transmission measurements made with these instruments.

Measurement of spectral characteristics (total spectral response as a function of detector spectral response, filter transmittance and lens spectral characteristics) were made for each transmissometer receiver. Figures 1, 2, and 3 provide results of this analysis.

Comparative field measurements were taken over a .5 km path during several days of testing. The transmissomters were all calibrated by bringing the receiver close to the source as per the Barnes calibration technique.

Table 1 compares statistics. In particular, the U.S. systems' measurements differ (up to 16% in the mean) from the European systems' measurements. Moreover, the deviations show spectral dependence.

Since these effects were not eliminated with the Barnes' close up calibration technique, a decision was made to (temporarily) calibrate against computed high transmittance values (LOWTRAN)

REFERENCE

Fenn, R., R. Toolin, and V. Turner, "Intercomparison Tests of the OPAQUE IR Transmissometer," AFGL Preliminary Report, November 1977.

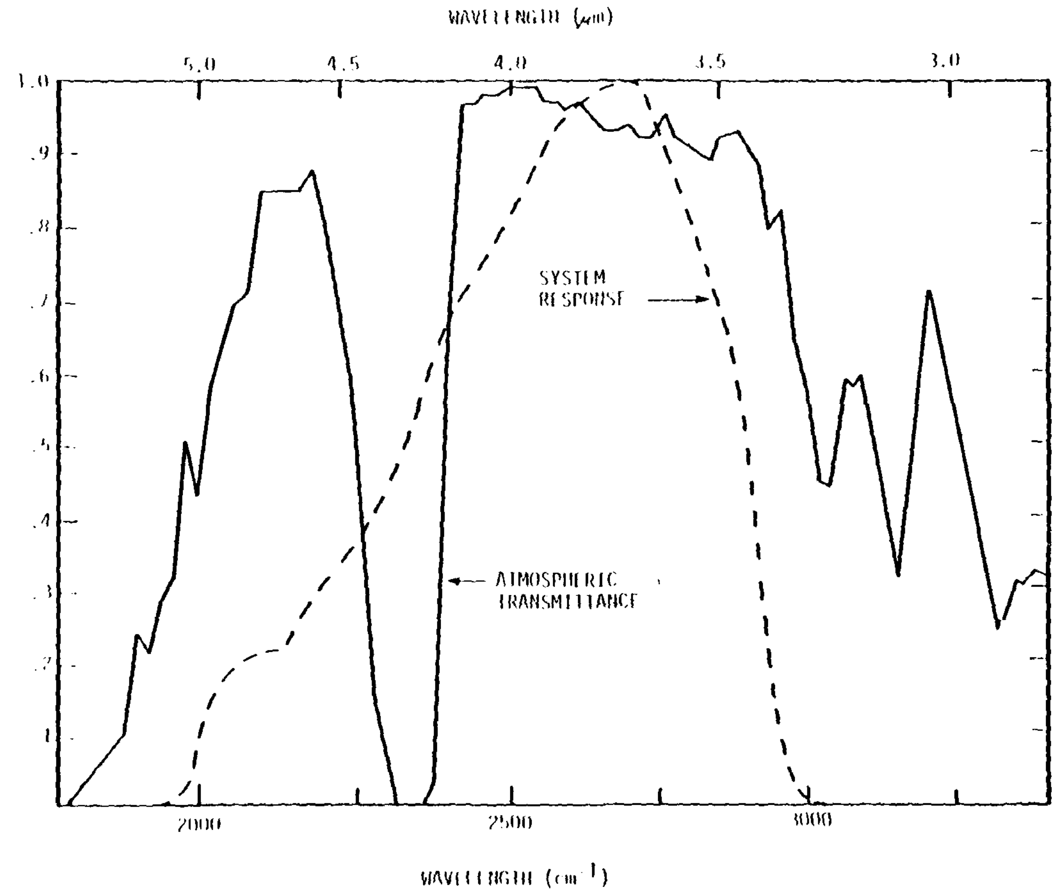

Figure 1. Typical Response and Atmospheric Transmittance.

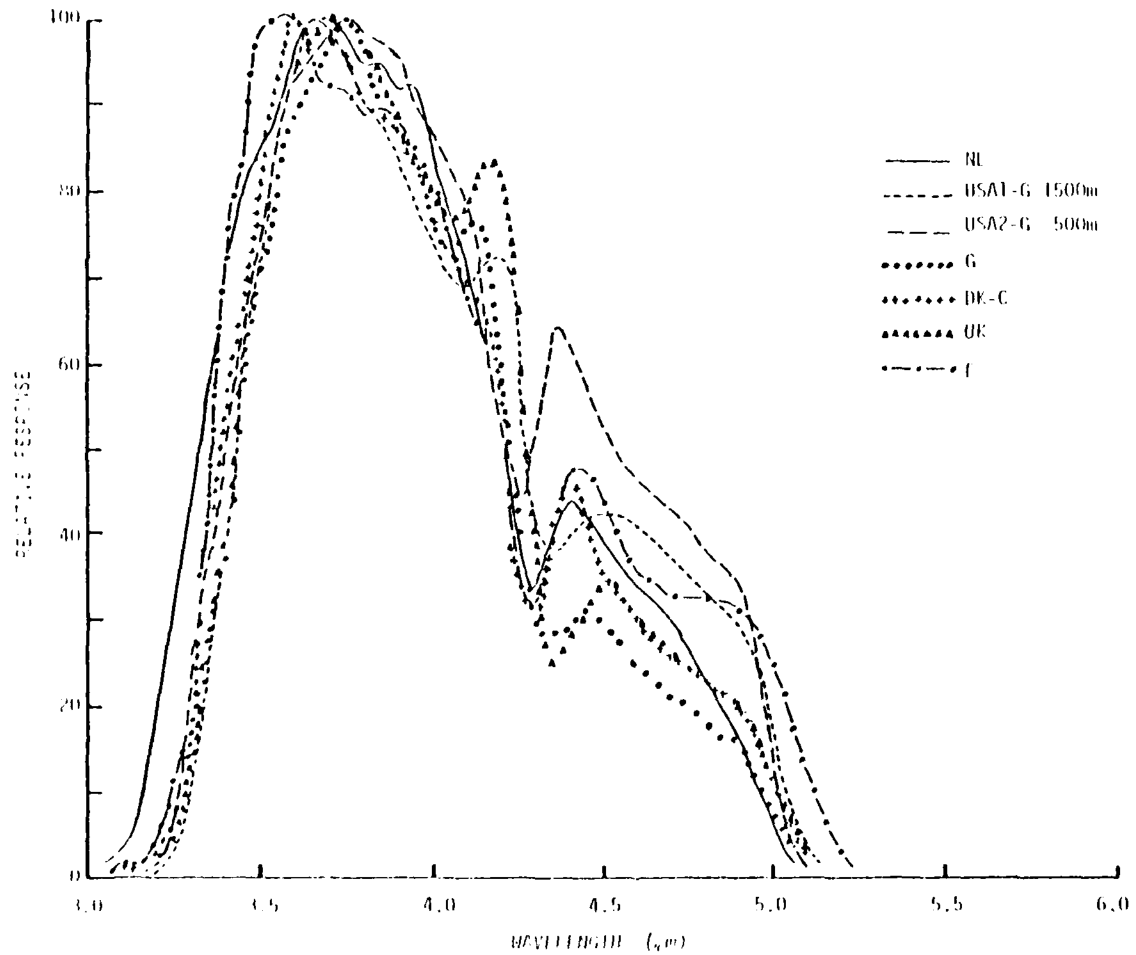

Figure 2. Spectral Response Curves of OPAQUE Barnes Transmissometer *Receivers, Measured with Netherlands Leiss Spectrograph.*

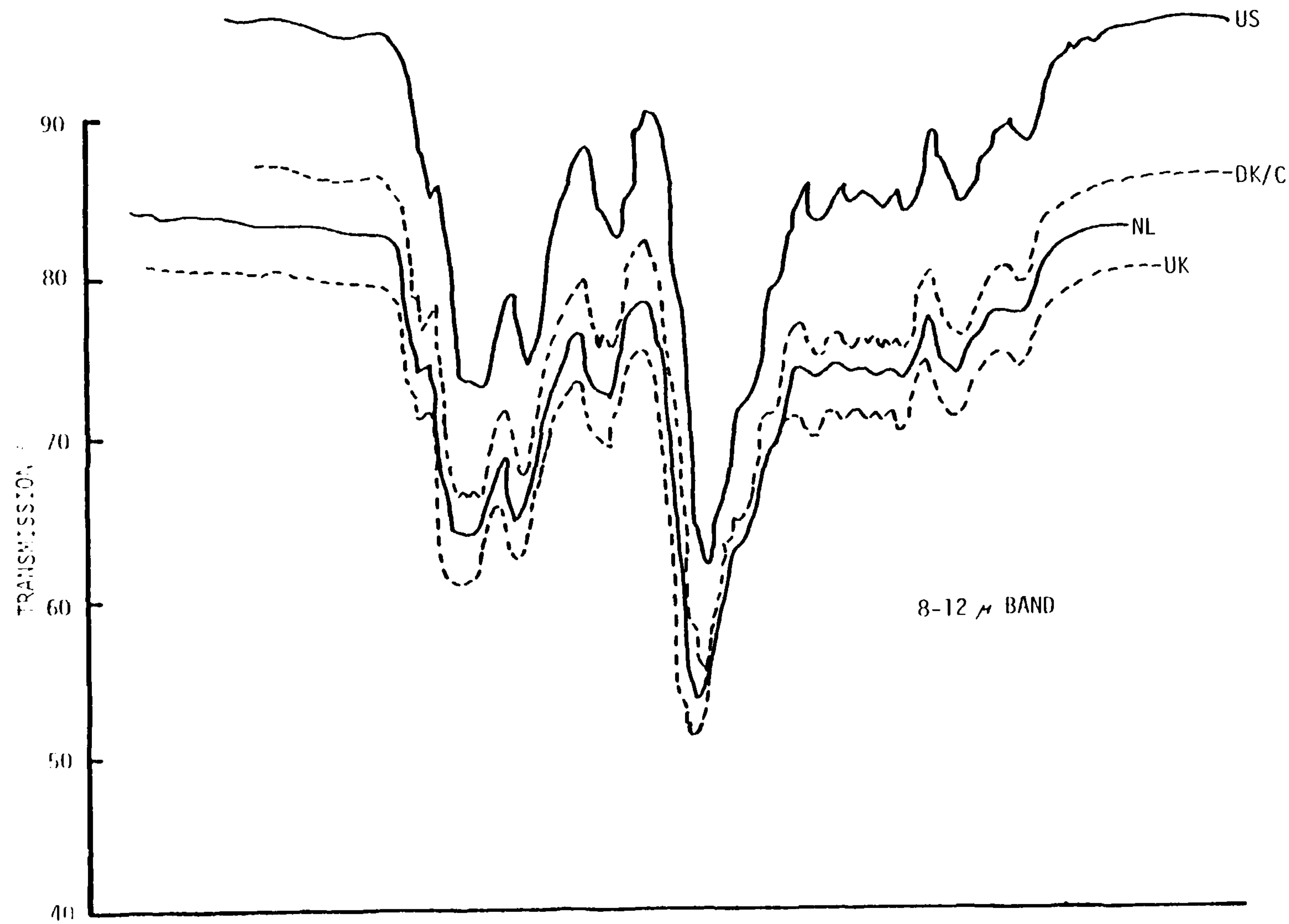

Figure [illegible]. Comparison of Relative Response of OPAQUE Barnes Transmissometers to Temporal Changes in Atmospheric Transmittance.

TABLE 1

COMPARISON OF BARNES TRANSMISSION MEASUREMENTS

18 September 1977, 15°°, Pershore, UK

BARNES TRANSMISSOMETER	% Transmittance over 500 m			
	3-5 μm		8-12 μm	
	Mean*	Stan. Dev.	Mean*	Stan. Dev.
Denmark	87.4	2.17	85.9	2.64
France	91.5	2.72	92.8	1.46
UK, repeat	83.1	3.86	84.4	2.33
Germany	83.8	2.93	89.4	2.23
Netherlands	84.7	2.1	83.4	2.28
UK	88.4	3.1	84.3	1.83
US 500 meter, repeat	91.4	2.81	99.6	2.39
US 500 meter	90.8	2.58	100.4	4.06

*Mean from 100 samples over 5 minute period.

ATMOSPHERIC TRANSMISSOMETER CALIBRATION

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Absolute measurements of radiant energy are very difficult to make. Therefore, when investigating a physical property such as atmospheric transmission, it is best if the measurement process does not depend on absolutes. Barnes' measurement method operates on the principle of determining the ratio of the irradiance actually received through the atmosphere from a source, to the radiance that would be received with the atmosphere removed.

The concept of calibration is that the receiver "see" a radiation source with the same angular subtense at both the calibration range of zero path length and at the selected operating range.

In the Barnes' calibration method, the source assembly is used in two ways. First, it is deployed at the desired range and used to make the transmission measurement. Second, it is placed close to and aligned with the receiver and used to make the calibration. In this second mode, an aperture is placed in front of the source in the collimator to simulate the same source angular subtense as the source at the range used during the measurement. Electrical attenuation can be used to compensate for energy level differences. The advantage of this method of calibration is that the atmosphere is effectively removed and that the identical source is "seen" at both the measuring and the calibration ranges.

Analysis

Now the measurement concept is stated and analyzed. The transmission measurement is based upon determining the ratio of the source radiation received through the atmosphere to the ratio that would be received with the atmosphere removed. This is expressed as:

$$T = \frac{RH_a}{RH_v} = \frac{TN_sA_c\, d^{-2}}{N_sA_a f^{-2}}$$

where

T = atmospheric transmission (dimensionless),

R = radiometer responsivity (volts $-cm^2$ $-w^{-1}$),

H_a = irradiance received through atmosphere (watts-cm^{-2}),

H_v = irradiance received through vacuum (watt -cm^{-2}),

N_s = source radiance (watts-cm^{-2}),

A_c = aperature of collimator mirror (cm^2),

d = distance to source (cm),

A_a = aperture area of source in collimator (cm^2), and

f = focal length of collimator mirror.

Now, of course, we cannot remove the atmosphere and receive H_V directly, but we can simulate H_V. Noting that $A_C\ d^{-2}$ is a solid angle, Ω_s, what we are really saying is that the quantity $N_s\Omega_s$ can be simulated to an accuracy better than the accuracy of a direct (absolute) measurement of the source radiance, N_s. By using the same real source at different distances, the source brightness can be completely unknown, and dependable values of transmission can be found.

The radiometer can be calibrated to read directly in percent T by setting R, the radiometer responsivity so that, while seeing the calibration source,

$$100 = R\ N_s\Omega_s$$

This normalizes the output so that the radiometer reads directly in percent transmission when viewing the range source.

When possible, it is desirable to use the same or identical sources for field or calibrations use. This is done in the systems supplied by Barnes. By using the ratio method, the absolute value of the source radiance does not affect system accuracy. In the Barnes system, only the stability of the system, the system noise, and the geometric and optical uncertainties in specifying the field solid angle of the source affect the accuracy.

Types of Errors

Only the major error sources in transmission measurements need be considered. The square root of the sum of the squares (RSS) of the individual errors will be used to express the total error for want of a better criterion. At this time, we will consider the 8-14 μm region only. The time period considered is of the order of several days.

Two fundamental types of errors are found. The first type is due to instabilities in the electronic components of the system, including signal-to-noise ratio, and can be divided into categories (a) through (d) below. This affects the accuracy of measuring low-level signals. The second type of error is due to uncertainty in measuring the optical dimensions involved when measuring 100% transmission during calibration and is considered as a geometric error. This affects the accuracy of measuring high-level signals.

(a) Source Radiance Variation - A variation of ± 5 kelvins under worst conditions is to be expected. This results in a percent radiance error of ± 1%.

(b) Electronics - Well designed, stable amplifiers are employed, with drift on the order of ± 0.25%.

(c) Detector Stability - ± 0.2%.

(d) System Noise - at 100 to 1 signal-to-noise ratio, ± 0.5%.

(e) Geometric Errors - These errors are systematic and can be calibrated out. A method of removing errors of this type is presented in the next section. Several typical geometric errors are included below.

Characteristic	Dimension	Typical Error	Percentage Error
Cal Aperture	0.003"	$\pm$0.00005"	3.3
Focal Length	25.6"	$\pm$0.0005"	0.04
Clear Aperture	4.075"	$\pm$0.0005"	0.03
Range	1 km	$\pm$1m	0.1

The root-sum-of-square error is dominated by the source uncertainty and is $\pm$1.145%.

IMPROVING CALIBRATION ACCURACY

Several procedures have been devised and suggested to improve calibration accuracy. These include a method for removing geometric error by making measurements at several ranges, and a proposed portable transfer radiometer to check calibration in the field. Each of these will be considered briefly.

Reduction of Geometric Error by Measuring at Several Ranges

Suppose when calibrating the radiometer by setting $100 = R\, N_s\, \Omega_s$, optical imperfections introduce an error so that $\Omega_s \neq A_s d^{-2}$. Then we can say that $\Omega_s + \varepsilon = A_s d^{-2}$. Now when we view the source at true range, d, we get:

$$\tau_\varepsilon = \frac{R\, N_s\, A_s\, d^{-2}\, \tau_t}{R\, N_s\, \Omega_s} = \left(1 + \frac{\varepsilon}{\Omega_s}\right) \tau_t \quad .$$

Here, τ_t is the true transmission and τ_ε is the erroneous reading.

By working on a clear day when conditions in the visible appear uniform over the pathlength, it is possible to determine this error experimentally.

A second reading is taken at range 2 d.

This will result in a new apparent transmission:

$$\tau_2 = \frac{R\, N_s\, A_s\, d^{-2}\, \tau_t^2}{4\, R\, N_s\, \Omega_s} \quad .$$

Note that the factor 4 appears from doubling the range and τ_t^2 is the square of the true transmission. We can substitute τ_ε in the equation for τ_2.

$$\tau_2 = \frac{\tau_\varepsilon\, \tau_t}{4} = \left(1 + \frac{\varepsilon}{\Omega_s}\right) \frac{\tau_t^2}{4} \quad .$$

If we multiply τ_2 by 4 and divide by τ_ε, we get:

$$\frac{4\,\tau_2}{\tau_\varepsilon} = \tau_t$$

Thus, by varying range, which can be very accurately measured, systematic calibration errors can be discovered. The method of course, depends on uniform transmission over the range.

An interesting point to notice is that the calibration error factor, $1 + \frac{\varepsilon}{\Omega_s}$, is constant. For example, at range 3 d:

$$\tau_3 = \frac{R\, N_s\, A_s\, d^{-2}\, \tau_t^{3}}{9\, R\, N_s\, \Omega_s} = \left(1 + \frac{\varepsilon}{\Omega_s}\right) \frac{\tau_t^{3}}{9}$$

Therefore, once the factor is known, it is applied to the apparent transmission in a simple manner, independent of range.

Reduction of Long-Term Error by Portable Transfer Radiometer

A portable transfer radiometer or transmissometer recalibrator is proposed to reduce long-term error. It provides a method for recalibrating a transmissometer system without removing the transmitter or receiver assemblies from their installations in the field. This is a most important savings in time and permits measurement programs to continue without significant interruption when a question concerning calibration arises.

The transmissometer recalibrator is a portable instrument consisting essentially of a small chopped source, a filter radiometer with excellent short-term stability, and a chargeable battery power supply capable of running the recalibrator for several hours. The battery is used only as a "keeper" during transport between the transmissometer source and receiver and from the user's home station.

The recalibrator is supplied with the values of two voltages, called V_c and V_t. These values are printed on the instrument for ready availability. The significance of these quantities will be explained below. We shall now step through the calibration procedure.

Before use in the field, the radiometer is self-calibrated against its own internal source and the radiometer is adjusted to produce an output V_c. The switch is left on and the instrument is carried to the transmitter assembly in the field. There it is plugged into the local power source and readjusted to produce V_c exactly when looking at its own source. The instrument then looks at the field source with its calibration aperture in place and records the output voltage as V_s.

Operating on its internal battery power, the recalibrator is carried to the receiver assembly, plugged into the local power and the recalibrator source

is adjusted, if necessary, to produce V_C. Now the transmissometer receiver looks at the recalibrator source and its output is adjusted, if necessary, to make its ouput equal to V_R where

$$V_s \times V_R/V_c = V_t$$

When this adjustment is made, the transmissometer system is effectively recalibrated.

CONCLUSIONS

The calibration method that has been described together with the certain adjustments and checks provide the most appropriate procedure that has been developed to date. Barnes Engineering Company does not express complete satisfaction with this method, but it has not yet received any suggestions for a better approach. Although the use of an evacuated chamber running the full length of the test range would provide a theoretically perfect calibration, such a facility is not expected to become available. A request is made for suggestions to improve calibration methods.

ATMOSPHERIC TRANSMISSION AT BLOCK ENGINEERING

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Block Engineering has longstanding interest in atmospheric transmission related efforts. In general, these have involved custom design of transmission measurement systems, use of Block owned equipment to make atmospheric transmission measurements in support of target and background signature measurements, as well as specialized research and development efforts.

Most of the equipment and measurements have involved interferometers of the Michelson type either used as source modulators or as spectroradiometers. Other systems have involved filter radiometers and multi-laser based systems of the wholly contained beam type. Design principles for these efforts include optical systems with oversized detectors and the use of field lenses to minimize alignment errors and scintillation effects. The overriding philosophy has been to make measurements at spectral resolutions as high as technically feasible and then to convolve them down to the requirement at hand.

Absolute calibration to the 100% line or vacuum transmission level has been approached in a number of ways. Among these are the use of a laser which is wholly contained within the receiver aperture, (a technique pioneered at NRL), multiple range measurements and normalization to clear bans using existing propagation models.

The use of a rapid scan Michelson interferometer as a source modulator has many advantages. Some of these are listed below.

- High efficiency, since only one step of modulation is used. No additional choppers or other forms of modulation are involved.
- High source chopping frequencies, which result in complete elimination of signals due to background and foreground radiation.
- High scan rate, giving virtually total immunity to atmospheric scintillation and source instabilities.
- Broadband spectral response limited by detector and beamsplitter response.
- Low dynamic range in each high speed interferogram scan, allowing recording by simple analog techniques without loss of significance in typical long term data recording sequences.

Its principle disadvantage is that throughput of the source is limited to what can be accepted by the interferometer, degrading the radiometric performance compared, for an example, with that obtained from a large chopped source. A set of spectra obtained with rapid scan interferometers are shown in Figures 1 and 2.

These were obtained in either a double-ended measurement configuration or as single-ended measurements using plane mirrors or retroreflectors. The spectral range is from 1 micron to 1 millimeter.

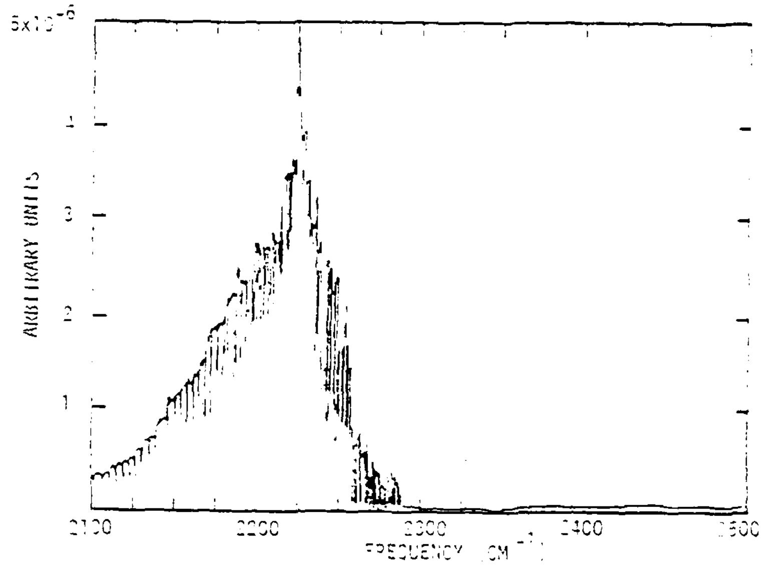
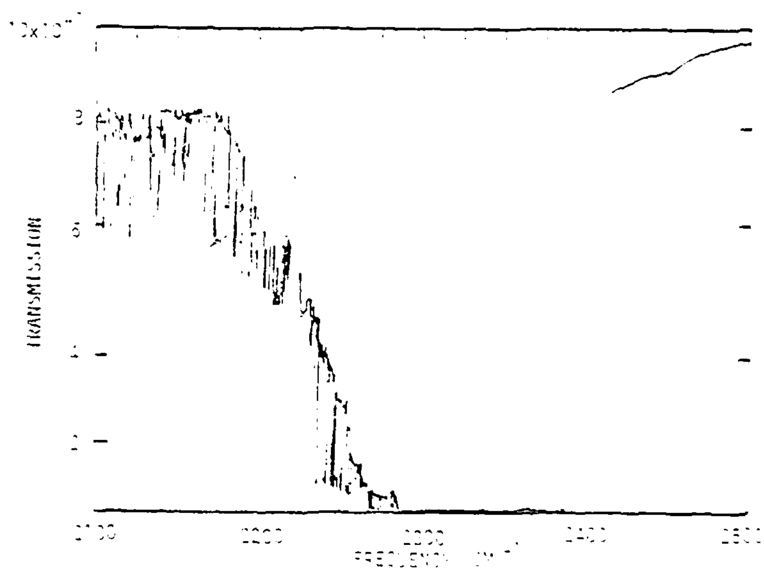


Figure 1a. Double-ended Measurement: Propane Flame Source (corrected for relative instrument response).



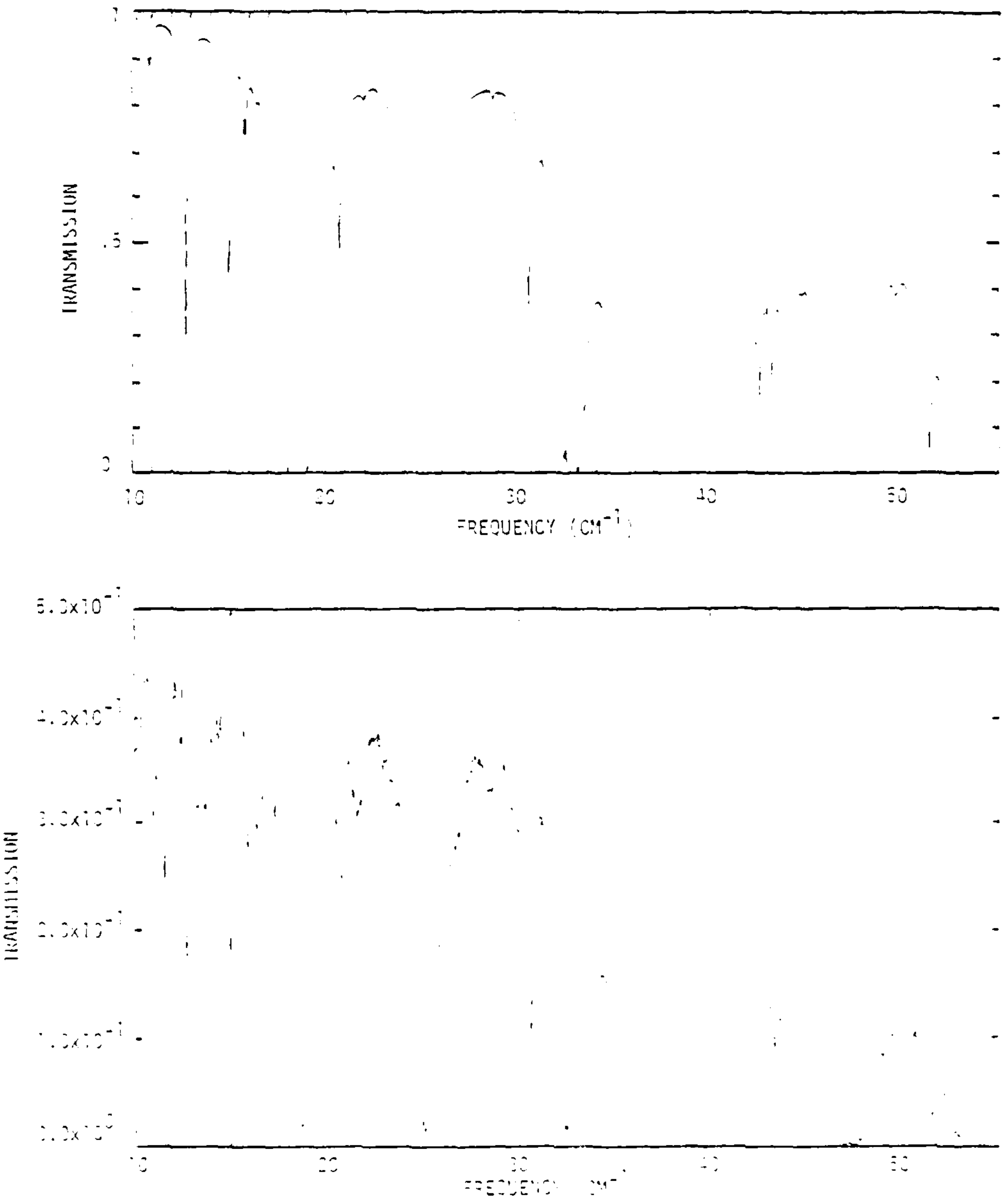


Figure 2. "Relative" Transmission For Computed ...

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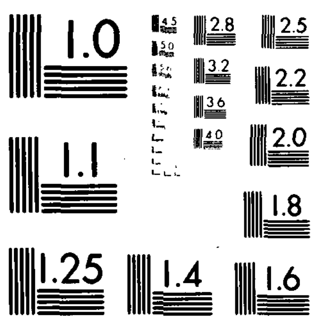

MICROCOPY RESOLUTION TEST CHART

ATMOSPHERIC TURBULENCE MEASUREMENT

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A series of atmospheric turbulence measurements were made in conjunction with the Airborne Laser Laboratory (ALL) program at the Air Force Weapons Laboratory. Of particular interest is the characterization of the refractive-index structure parameter C_n^2 via measurement of the temperature structure parameter C_t^2.

An operational technique for measuring C_t^2 (and thus C_n^2) from high-altitude aircraft was developed. It utilized hot-wire anemometer probes to measure the temperature fluctuations. By utilizing two probes at different overheat ratios and reducing the data simultaneously by spectral analysis it is possible to separate the temperature fluctuation effects from velocity effects in a noise-resistant fashion. This becomes important at high altitudes.

The present data base is growing but is yet grossly inadequate for application. The data are not correlated with meteorological and orographic observables; future experiments are needed to relate these to measured turbulence parameters.

Initial probe designs were by L. E. Pape with analysis by S. A. Collins, Jr. and Y. S. Liu; more recent designs were by W. C. Rose with analysis by C. A. Levis and J. P. Serafin.

IDEALLY TRANSMITTED BEAM

TURBULENCE-INDUCED BEAM BREAKUP, RESULTING IN EXCESS AVERAGE ATTENUATION. MANY INSTRUMENTS DO NOT DISCRIMINATE BETWEEN TURBULENCE-INDUCED ATTENUATION AND THAT DUE TO ABSORPTION AND SCATTERING.

Figure 1. Problem: Typical Turbulence Effects on a Light Beam.

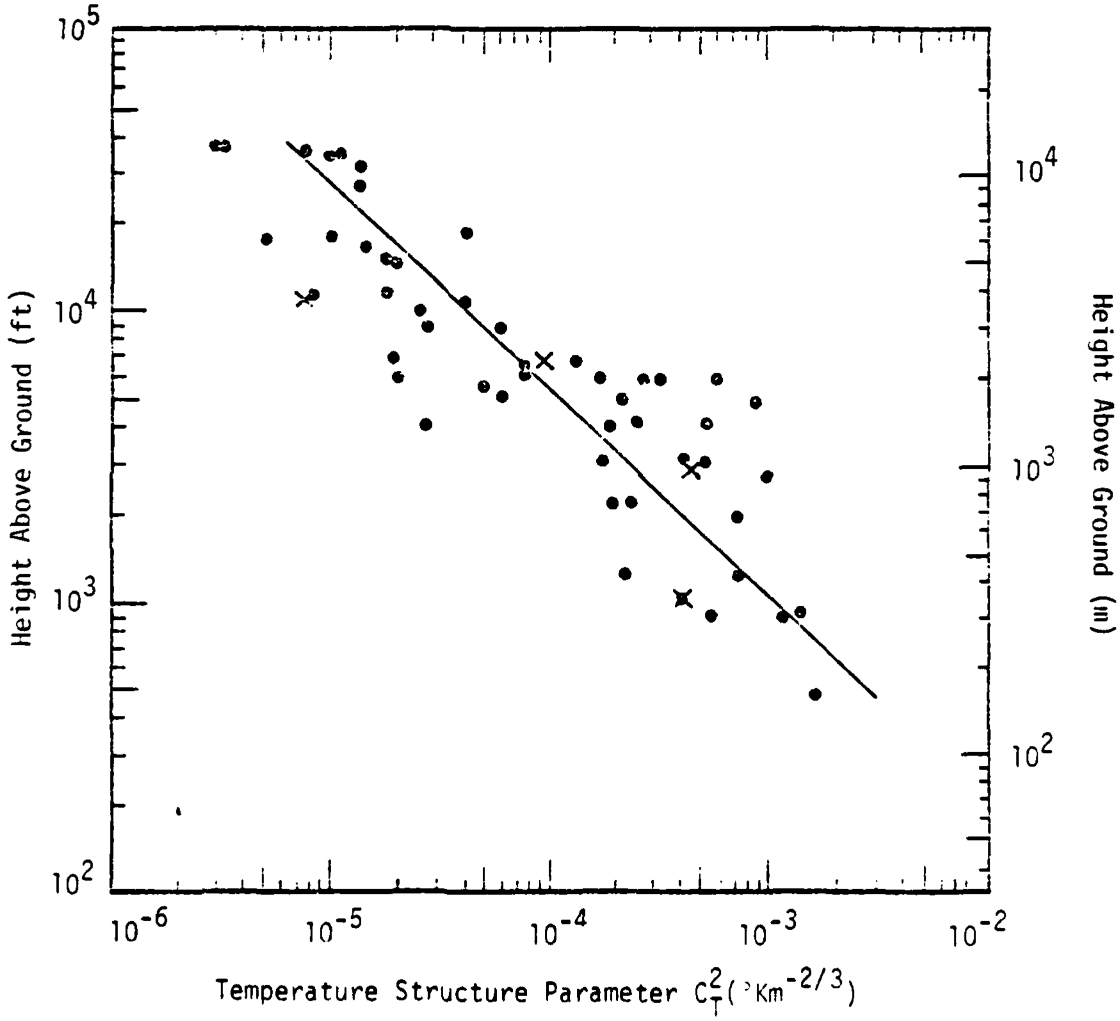

Figure 2. C_T^2 with Height. (The X's indicate measurements made over a 2-hour period in one location under stable conditions.)

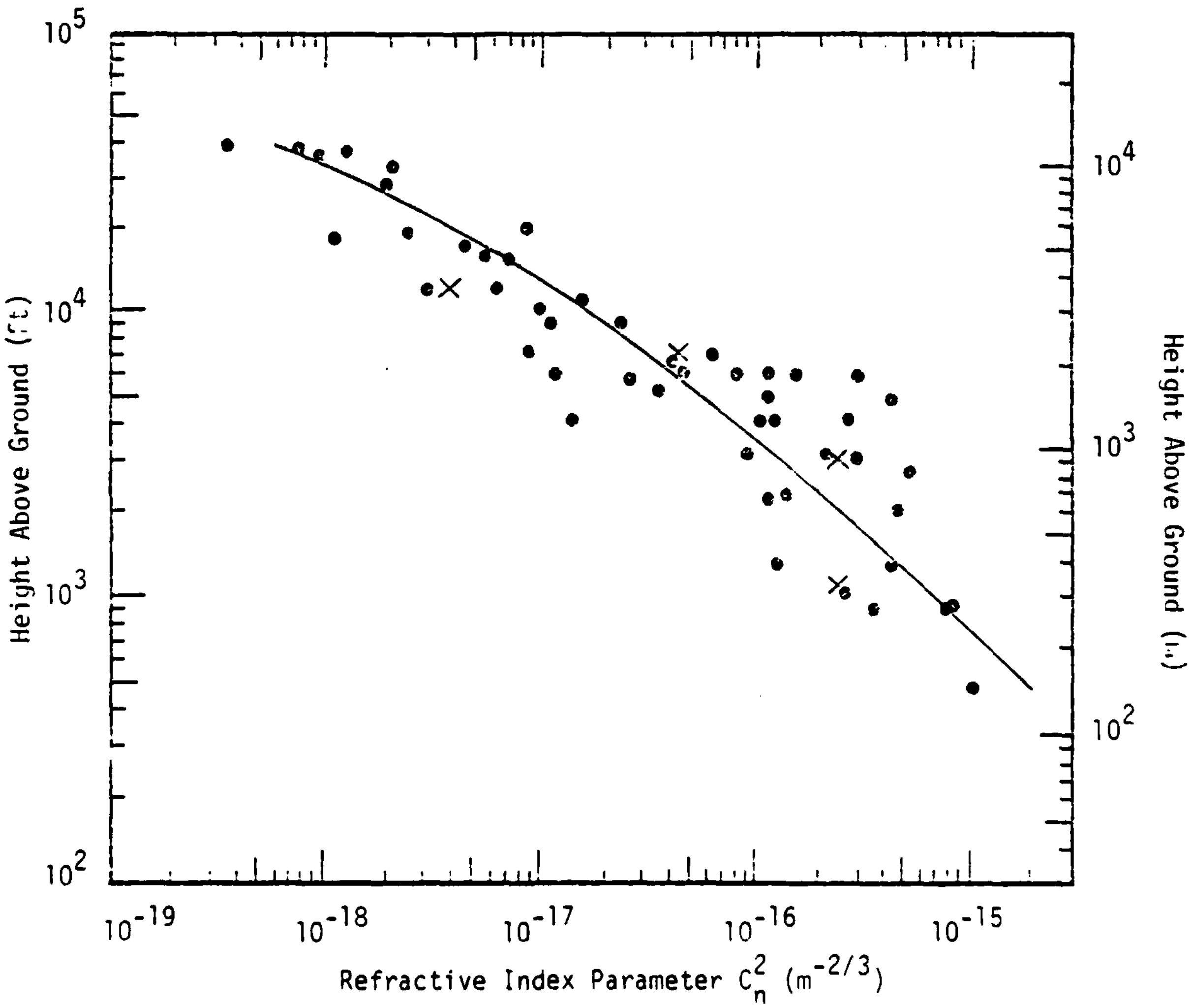

Figure 3. C_n^2 with Height. (The X's indicate measurements made over a 2-hour period in one location under stable conditions.)

ADVERSE METEOROLOGICAL EFFECTS ON ATMOSPHERIC TRANSMISSION

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MOISTURE VARIABILITY

Moisture variability in the atmosphere is much greater than is generally realized, and causes difficulty with transmissometer evaluation in the real atmosphere. It is especially troublesome when attempting to verify atmospheric transmission models, and also when attempting to reconcile EO system performance with on-going meteorological conditions.

The solar radiometer has only recently been recognized as a valuable moisture monitor (Volz, AFGL, 1974, Pitts, et al., NASA/JSC, 1977). The principle of operation is the ratioing of solar transmissions in two adjacent IR bands, only one of which is subject to strong water vapor absorption. The two wavelengths respond equally to all other constituents.

A brief review of published data collected by means of these radiometers points out an obvious need for more measurements of this nature to establish spatial and temporal variations of precipitable water for a variety of climates.

Figures 1-3 are recordings of precipitable water made by NASA's DeMonbrun autotracking radiometer system. These traces reveal fine structure, since they are derived from continuous recordings. A temporally fluctuating precipitable water trace is evident in all cases.

Decreases in precipitable water sometimes, but not always, coincide with sudden increases in optical depth at other wavelengths. This suggests that an interaction of moisture with particulates to form a disperse droplet population (invisible cloud) may be responsible for the fluctuation. This can occur in a layer of atmosphere where the relative humidity is 80% or more (Wilkins, 1976) with optical depth changes of the kind seen here.

The fast response and continuous recording mode of the DeMonbrun system make it possible to examine the moisture structure for scales on the order of one second or smaller. This was done for selected one-minute intervals of the 31 March (Figure 2) recording. Means and standard deviations for twelve one-minute intervals are given in Table 1. Comparison with the trace of Figure 2 shows that the standard deviations are generally less than 1% of the mean except for the one-minute intervals taken during periods of large variability such as the first two and the one taken at 10:50 AM. For these the standard deviation is 3-5%, which is very large for so short a time scale. The statistics at 10:58 AM are based on 85 individual readings during the one-minute period.

In summary, then, the temporal variability of total precipitable water, based on the limited data base available, appears to relate to time scale as follows.

TIME SCALE	VARIABILITY
0.5-2 second	1-5% of mean
1 minute	8-12%
20 minutes	15-20%
1 hour	25-50%
4 hours	100-200%

Since no attempt was made to select periods which would maximize the moisture variability there is no reason to believe that even larger extremes do not occur. The temporal variability gives a clue to spatial variability, since much of the observed variation must be due to structure swept past by the wind.

It should be emphasized that these dramatic moisture events may occur entirely during clear skies and are not predictable on the basis of any current forecasting technology.

TRANSMISSION MEASUREMENTS VERSUS MODEL PREDICTIONS

Because of the difficulty in describing the moisture content of the atmosphere at any place and time there will always be considerable uncertainty in the assessment of EO system effectiveness. This uncertainty is not due to lack of knowledge about moisture transmission, but it is aggravated by moisture variability and sensitivity of the system. The LOWTRAN transmission model will yield good results if the variability is averaged out, if particulate interactions with moisture are small, and if the moisture concentration is not too high.

Figure 4 gives a comparison of theory with actual 8-12 μm transmissometer measurements (Bergemann, 1977) in moist atmospheres. The dash line represents perfect agreement. There is considerable scatter about this line, and the largest error is by a factor of two. Most of this scatter is due to the inability of the moisture sensors to adequately define the moisture path in the presence of spatial and temporal variability. The scatter in Figure 4 is reasonably symmetrical, and absence of bias in high moisture situations lends some confidence to the use of the LOWTRAN model. At least, the limitations are fairly well identified.

The transmissometer range at Eglin Air Force Base used by Bergemann is very well instrumented, and attempts were made to relate the transmission measurements to various meteorological parameters. Table 2 lists both measured and computed attenuation coefficients for a variety of visual ranges between 9.5 km and 24 km. Several important points must be emphasized from these results.

(1) There is a fair correlation between visual range and transmittance, but attempting to account for the other meteorological variables does not improve the relationship between measured and predicted attenuation coefficients.

(2) Although no haze was reported, the attenuation coefficients are comparable to those measured under moderate haze conditions.

(3) The measured attenuation is almost invariably greater than predicted, but the largest discrepancies occurred for relative humidity in excess of 77%. This could be caused by a small population of droplets which would not have been taken into account by the LOWTRAN model.

When aerosols and/or water droplets are an important contributor to attenuation, the situation becomes much worse. Mie theory computations using various particle size distributions of haze, fog, clouds, and precipitation are useful for ball-park estimates, but they do not fare very well in field trials. The Hannover, Germany experiments (Biberman, et al., 1977) were very revealing in this regard. For "well behaved" data, meaning a relatively clean and dry atmosphere, the transmissometer measurements were in agreement with LOWTRAN within ±3% for 85% of the time and within 6% for 95% of the time. However, for the aggregate of all of the transmissometer measurements the comparison with the model was described as follows.

one third - ±5% (accurate)

one third - ±15% (fair)

one third - "wild"

These observations give us an idea of the portion of the time that tests may be performed without undue interference by meteorological factors.

EFFECTS OF HAZE AND FOG

The marine atmosphere of the Atlantic Ocean invades Europe to an average height of 5 km during most of the time. The probabilities that haze conditions will be equal to or worse than average, hazy or heavy haze conditions at Berlin are given as follows:

	Average	Hazy	Heavy Haze
Visibility	32km	7 km	4 km
Prob. for Dec-Jan	99%	60%	50%
Prob. for June-July	85%	10%	5%

These statistics (Wilkins, 1979) present a rather grim picture. By using the climatological average moisture content for these visibility limits and the mid-season months we can construct a table of attenuation coefficients for 10.6 μm radiation such as Table 3, which does not take into account the interactions of particulates with the atmospheric moisture. As a result, the attenuation coefficients are unrealistically low in July, when the moisture content is highest, and also in heavy haze, where the aerosol-moisture interactions are almost invariably present.

Table 4 gives averages of the attenuation coefficients for actual measurements of IR radiation via transmissometer near Hannover, Germany. The ranges were 1180 m and 4310 m long and were instrumented for temperature, humidity, and aerosol counts, as well as for quantitative measurements of visual range. Here, the increased attenuation due to greater moisture-aerosol interaction in summer haze is quite obvious. The simple combination of a haze model with a moisture model does not suffice to predict haze attenuation.

These measurements show an increase of about 8 dB/km between heavy marine haze and light fog. The data also showed that this increase is dependent more on the total moisture content than on changes in droplet size distribution. However, it must be remembered that the two are closely related, and also, accurate measurements of droplet size distribution are impossible with available instrumentation. The true relationship of attenuation to particle size distribution is not really known, although theoretical models indicate considerable sensitivity.

The Hannover experiments also showed that point-to-point transmission measurements at ground level do not necessarily reveal the true situation for slant range approaches. Balloon sounding made during haze and fog conditions showed that the water content (and the corresponding IR attenuation) very often increases with height in the lowest 200 m. Figure 5 gives samples of mositure soundings and the corresponding (calculated) extinction coefficients at three wavelengths (Biberman, et al., 1977). Aerosol and droplet models were used for the extinction calculations.

For the haze situations of 2/28/76, the extinction coefficient is essentially independent of height, but the three fog situations show significant increases with height. There is no reason to suppose that this condition is restricted to the Hannover region, and so further investigations are badly needed.

EFFECTS OF CLOUDS AND PRECIPITATION

Wilkins (1979) has compiled statistics on the risk of encountering each of the nine basic types of clouds over Europe and the Atlantic Ocean, and has given backscatter and attenuation coefficients for each type in 10.6 μm and 3 mm wavelengths. The statistics are broken down by season and time of day. The study shows that the probability of a cloud-free line-of-sight (P/CFLOS) is very low, especially in winter, for flights at altitudes above 300 m. Even in partially cloudy conditions the P/CFLOS is very low for typical aircraft speeds if acquisition time is one second or longer.

Tables 5 and 6 give the consequences of these weather elements in terms of albedo and extinction coefficients at 10.6 μm and 3 mm. Cumuliform and stratiform clouds and accompanying precipitation are dealt with separately, and rainfall rates peculiar to each type are given. The models (Gaut and Reifenstein, 1971) are segmented into layers according to different water densities and droplet sizes typical for each range of altitude given.

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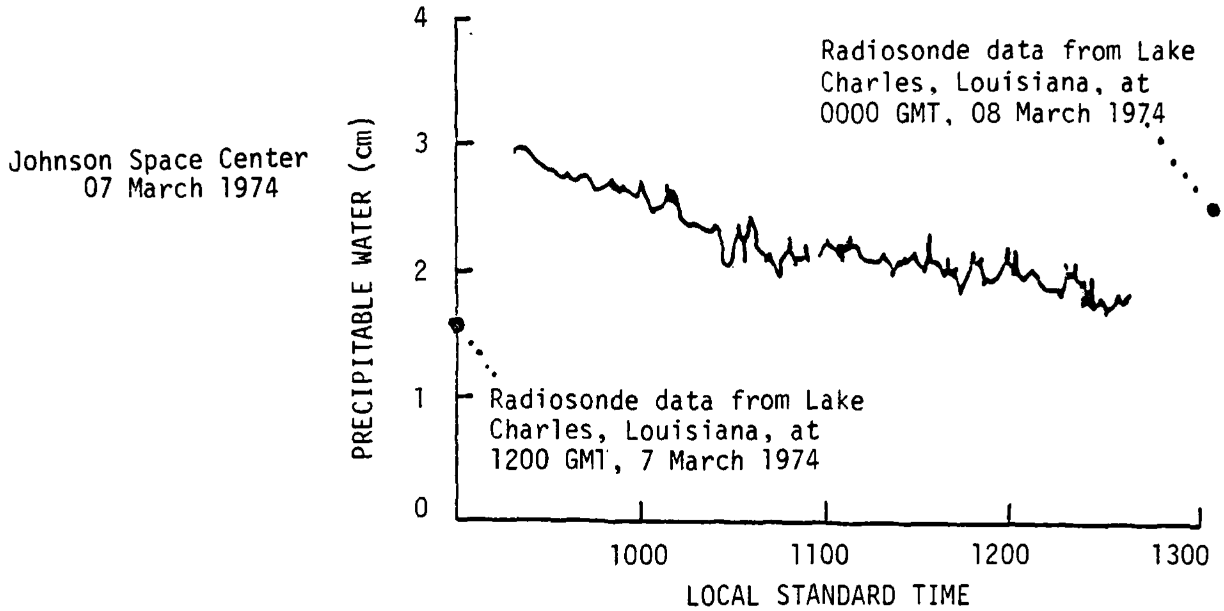


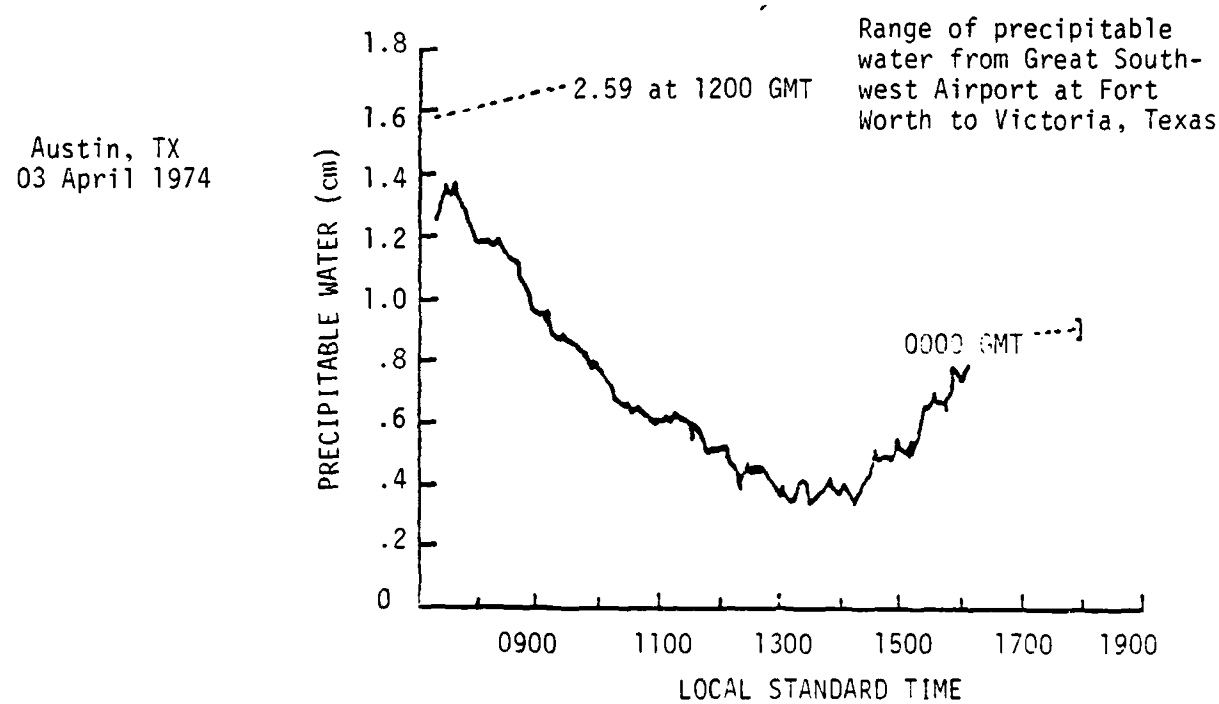
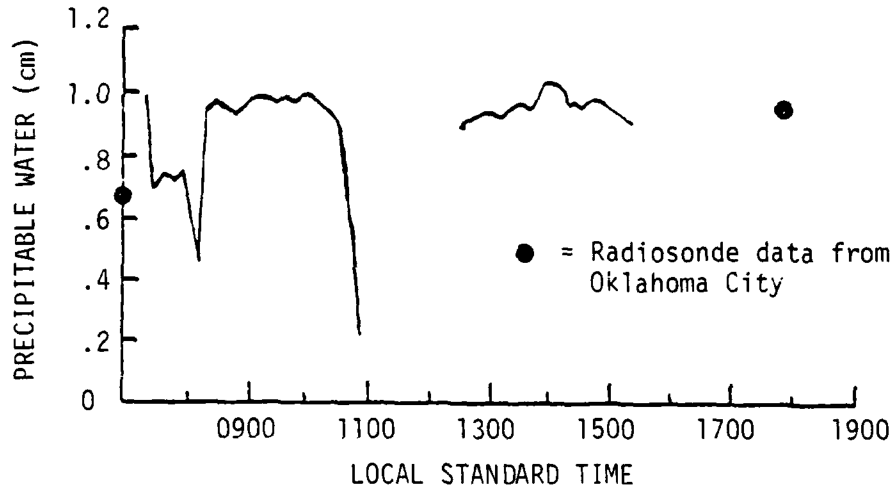


Figure 1. Total Atmospheric Precipitable Water Traces Measured in Texas by the DeMonbrun System (Pitts et al., 1977).

31 March 1975



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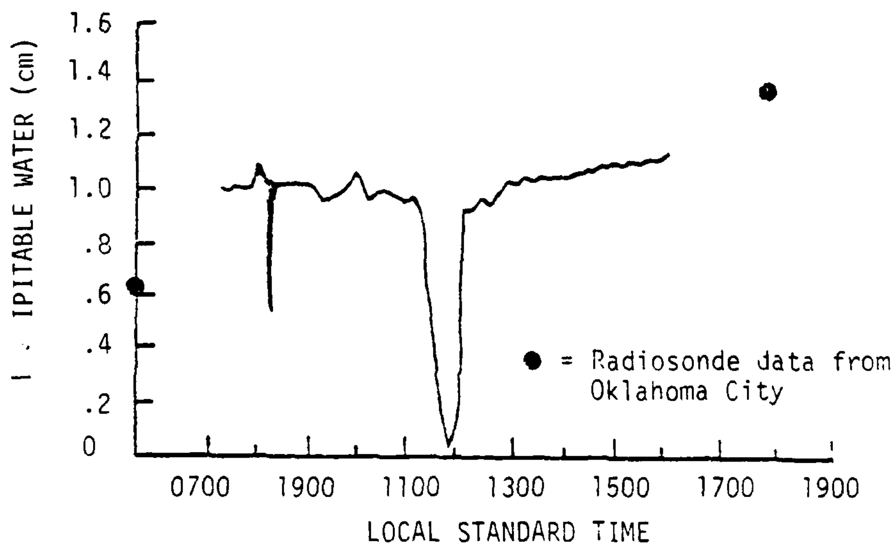

Figure 2. Continuous Traces of Total Atmospheric Precipitable Water as Monitored by a NASA DeMonbrun Suntracking Radiometer at Norman, Oklahoma (Pitts et al., 1977).

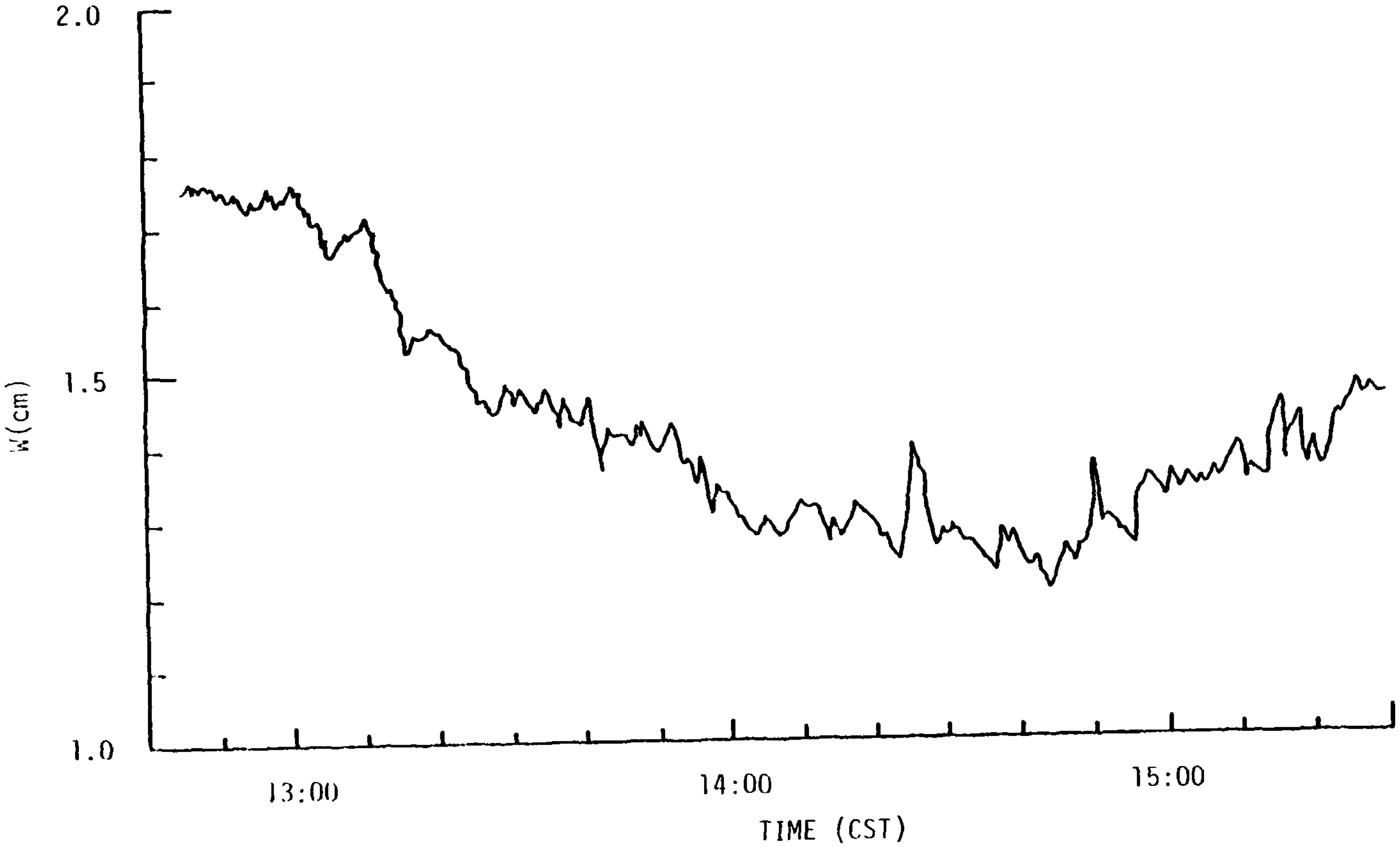

Figure 3. Time Graph of Total Precipitable Water W at Norman, Oklahoma, September 1974 as Monitored by the NASA DeMonbrun System (Wilkins, 1977).

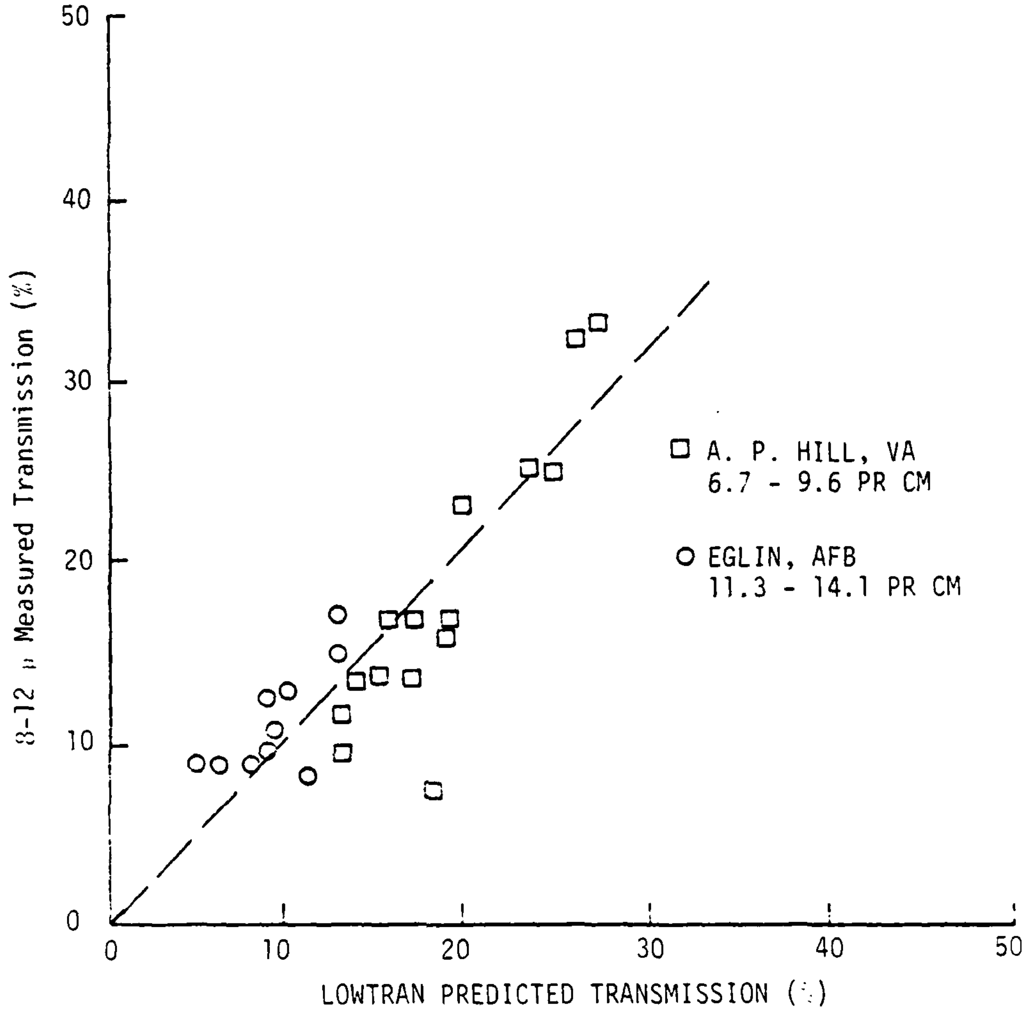

Figure 4. Comparison of 8-12 μm Transmission Through High Precipitable Water Concentrations with LOWTRAN IIIa Predictions (Bergemann, 1977).

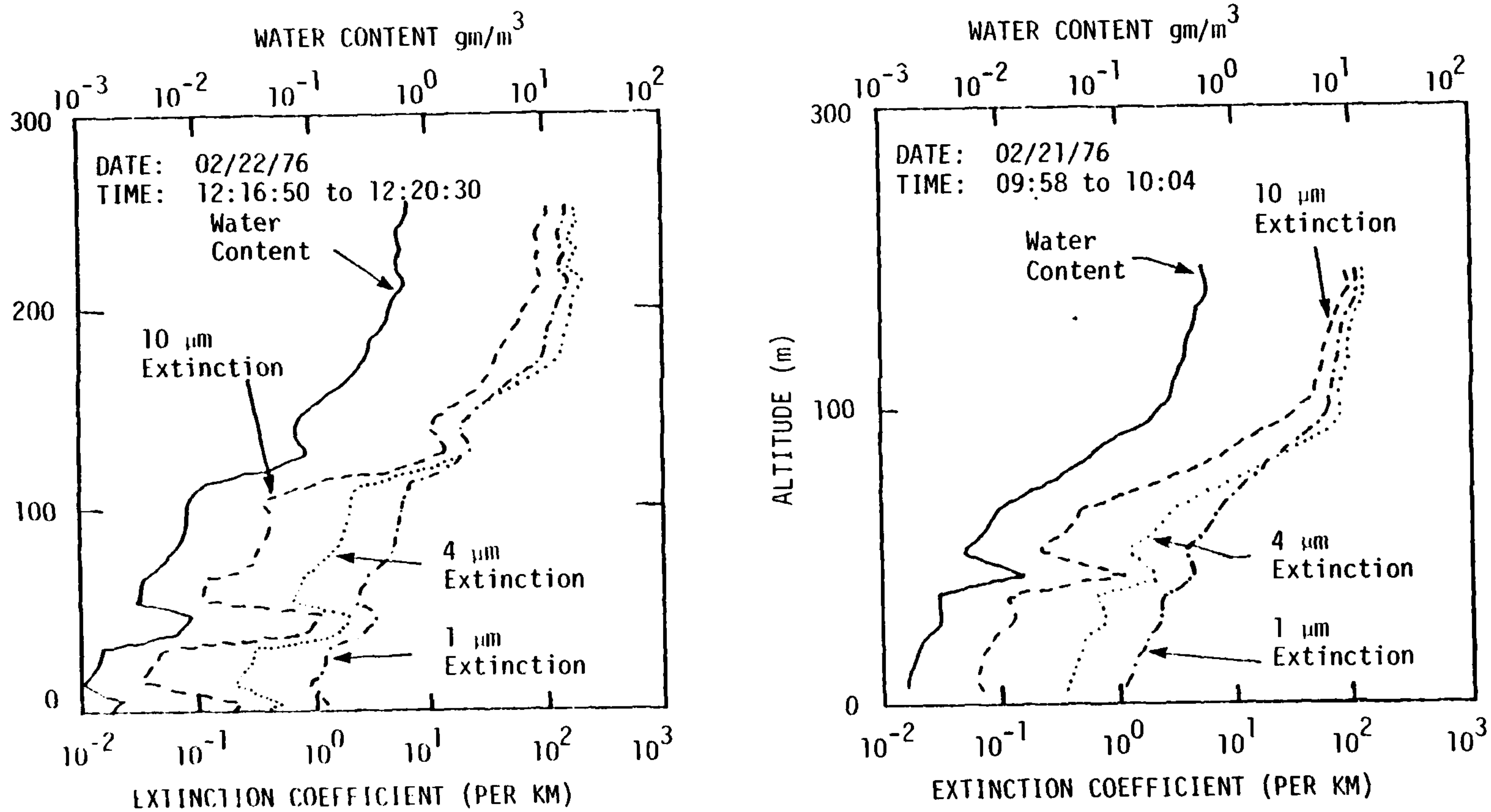

Figure 5. Effect of Altitude Upon Extinction Coefficient of Fog Droplets and Aerosols for Four Sets of Measured Data at Grafenwöhr, Germany.

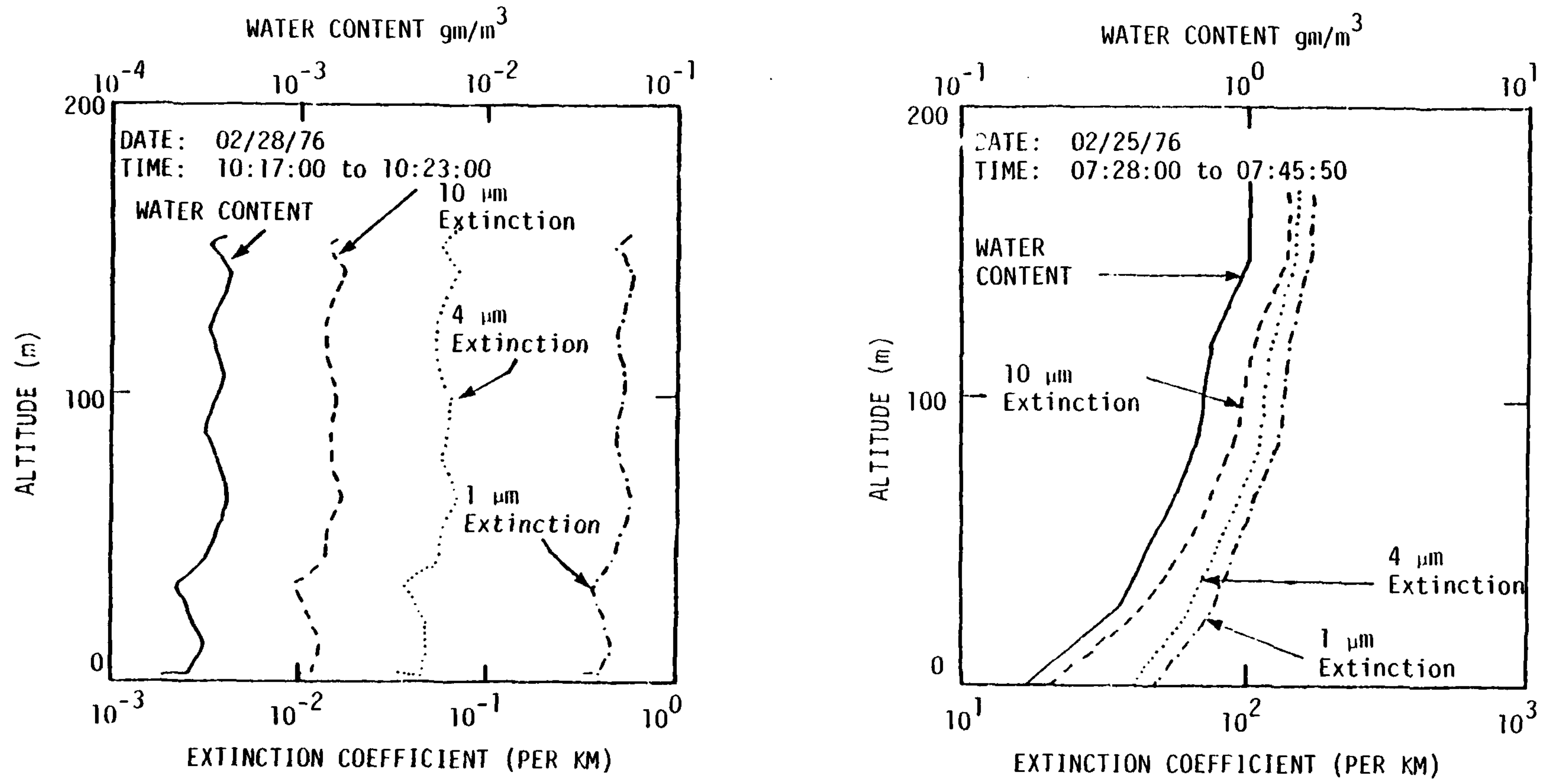

Figure 5 (Cont'd). Effect of Altitude Upon Extinction Coefficient of Fog Droplets and Aerosols for Four Sets of Measured Data at Grafenwöhr, Germany.

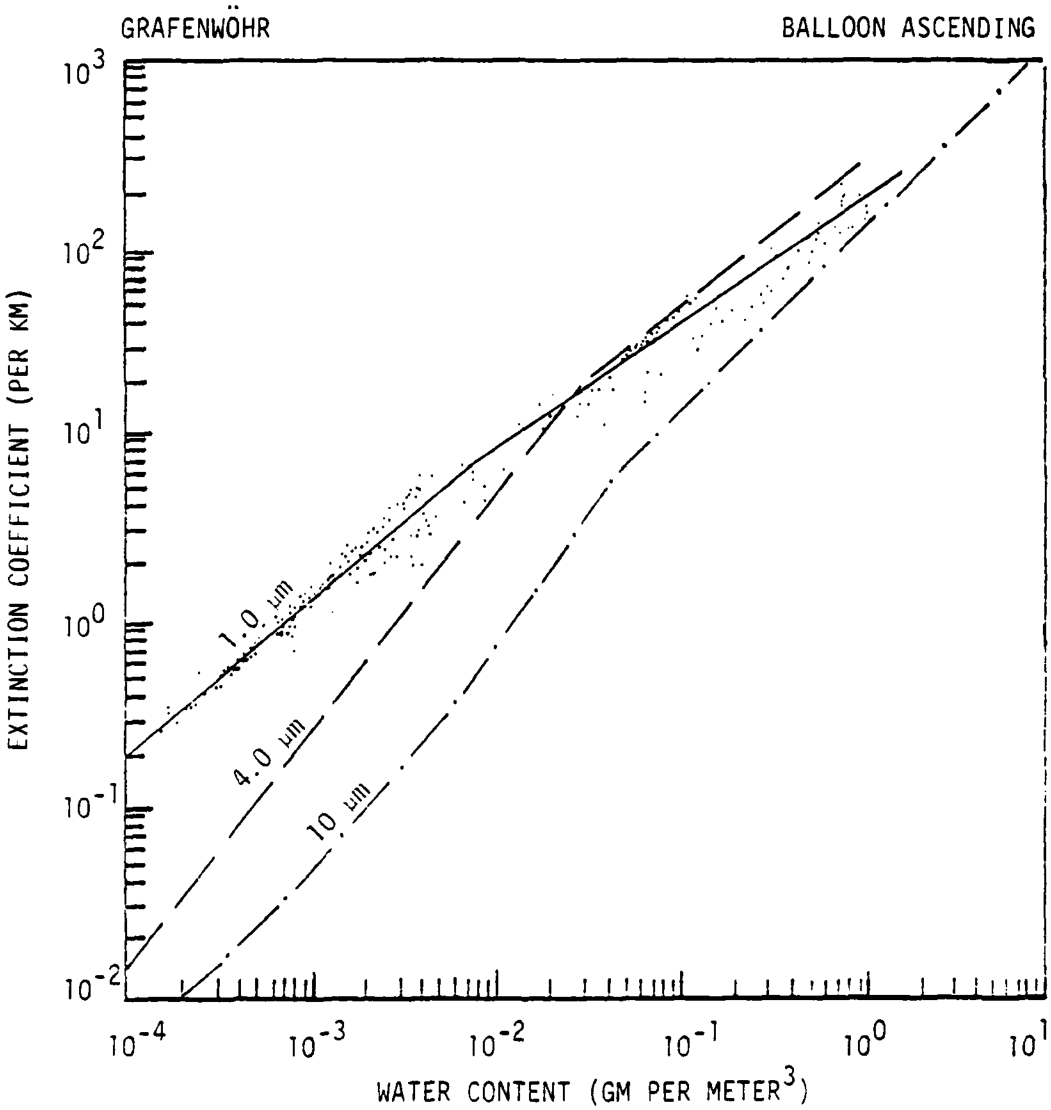

Figure 6. Extinction coefficients (for fog situations) in three wavelengths versus liquid water content of fog droplets. The data was collected through balloon ascents at Grafenwöhr, Germany. Curves for 4 μm and 10 μm were constructed for data plots similar to that for the 1.0 μm curve.

TABLE 1

PRECIPITATION WATER STATISTICS FOR TWELVE 1-MIN. INTERVALS AT NORMAN, OK 3/31/75

TIME	NO. READINGS	AV. P.W.	STD. DEV.	% VARIATION
07:36 CTS	13	1.0085 cm.	.0489 cm.	4.85%
07:37	27	.9042	.0315	3.48
08:29	40	.9250	.0028	0.30
08:30	65	.9275	.00306	0.33
09:34	69	.9772	.00496	0.51
10:58	85	.1788	.00612	3.42
13:08	120	.9053	.00637	.70
13:43	72	.9310	.00709	.76
14:28	31	.9059	.00636	.70
14:29	55	.9236	.00503	.54
15:30	38	.8535	.00339	.40
15:31	88	.8645	.00817	.94

TABLE 2

ATTENUATION COEFFICIENTS FOR 8.1-12 μm RADIATION MEASURED AT EGLIN AIR FORCE BASE AT VARIOUS VISUAL RANGES, COMPARED WITH LOWTRAN III-a COMPUTATIONS*

VISUAL RANGE	PRECIP. WATER	TEMPERATURE	RELATIVE HUMIDITY	ATTENUATION MEASURED	COEFFICIENT PREDICTED
24 km	1.67 cm/km	32.5°C	48%	1.21 dB/km	1.07 dB/km
21.2	1.64	31.5	50	1.21	1.15
18.0	1.73	27.0	67	1.43	1.25
16.6	1.78	29.0	62	1.43	1.41
13.7	1.68	21.8	86	1.43	1.36
12.6	1.93	26.5	77	1.78	1.45
12.6	1.85	23.8	86	1.67	1.45
12.3	1.71	22.0	88	1.50	1.47
9.5	1.55	23.0	75	1.31	1.55

*Measurements made in July, 1976

TABLE 3

SCATTERING ATTENUATION OF 10.6 μm RADIATION OVER EASTERN EUROPE DUE TO HAZE*

	VISUAL RANGE	JAN	APRIL	JULY	OCT
Average Haze	32 km	1.26	1.29	1.34	1.30 dB/km
Hazy	7 km	1.53	1.56	1.61	1.57
Heavy Haze	4 km	1.71	1.74	1.79	1.75

*Computed by adding average monthly water vapor attenuation to particulate scattering. Point-to-point at ground level.

TABLE 4

ATTENUATION COEFFICIENTS MEASURED IN HAZE AND FOG AT 8.1-12 μm GRAFENWÖHR, GERMANY, 1975-76*

	VISUAL RANGE	WINTER	SUMMER
Haze	5 km	0.81 dB/km	2.76 dB/km
Light Fog	1 km	9.21	10.6
Moderate Fog	0.67 km	16.2	18.5
Heavy Fog	0.33 km	43.2	49.3

*Reported by Bergemann (1977)

TABLE 5

EXTINCTION COEFFICIENTS AND ALBEDOS FOR PRECIPITATION FROM CUMULIFORM CLOUDS

		10.6 μm Radiation		3 mm Radiation	
Related Element	Altitude Range	Ext. Coeff (dB/km)	Albedo	Ext. Coeff (dB/km)	Albedo
Cumulonimbus	8-10 km	14.7	50%	14.5	0.4%
with rain	6-8	177	52	47.9	23
(150 mm/hr)	4-6	237	52	63.9	23
	1-4	474	52	128	23
	0.3-1	201	51	17.4	41
	0-0.3*	7.61	51	8.2	61
Cumulus	1-4	237	52	63.9	23
with rain	0.4-1	57.5	51	48.9	41
(12 mm/hr)	0-0.4*	3.17	51	3.83	56
Cumulus	1-3	118	52	31.9	23
with rain	0.5-1	28.7	51	24.9	41
(2.4 mm/hr)	0-0.5*	1.64	52	1.85	56
Cumulus Conjestus	2.5-3	31.9	50	21.0	38
(no rain)	2-2.5	63.8	50	42.1	38
	1.6-2	51.0	50	33.7	38
	1.2-1.6	68.6	52	13.8	22
	1-1.2	100	59	4.83	2.5
Altocumulus	2.4-2.7	50.2	59	2.42	2.5
Stratocumulus	0.3-1.2	83.7	59	4.03	2.5
Cumulus	0.5-1	167	59	8.0	2.5
Humilis	1-1.5	335	59	16.1	2.5
	1.5-2	167	59	8.0	2.5

*Rain shaft only, no clouds

TABLE 6

EXTINCTION COEFFICIENTS AND ALBEDOS FOR PRECIPITATION FROM STRATIFORM CLOUDS

Related Element	Altitude Range	10.6 μm Radiation Ext. Coeff (dB/km)	10.6 μm Radiation Albedo	3 mm Radiation Ext. Coeff (dB/km)	3 mm Radiation Albedo
Steady Rain	2-4 km	670	59%	32.2	2.5%
(15 mm/hour)	1-2	1,000	59	48.3	2.5
	0.3-1	670	59	32.2	2.5
	0-0.3*	12.7	51	16.7	52
Rain	1-1.5	335	59	16.1	2.5
(3 mm/hour)	0.5-1	670	59	32.2	2.5
	0.15-0.5	335	59	16.1	2.5
	0-0.15*	2.5	51	3.3	52
Drizzle	1-1.5	335	59	16.1	2.5
(0.2 mm/hour)	0.5-1	670	59	32.2	2.5
	0-0.5*	154	52	23.0	14
Cirrostatus	4.6-6.4	7.4	50	1.55	nil
Altostratus	2.4-3.5	84.0	65	2.22	0.4
Stratus	0.15-0.91	140	65	3.69	0.4
Frontal Fog	0-0.05	51.2	57	2.28	1.0
Heavy Haze	--	2.48	20	1.31	0.0

*Rain shaft only, no clouds

ASTRONOMICAL EXTINCTION MEASUREMENT AND ATMOSPHERIC TRANSMISSION

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Atmospheric transmission (in the visible part of the spectrum) has been measured routinely using astronomical techniques since the turn of the century. During the last 10 years our group at Lawrence Livermore Laboratory has been using multispectral astronomical extinction measurements to unfold pollution and meteorological parameters. Our work has shown two important results that modelers and experimentalists in atmospheric transmission should be aware of. First, evidence is quite strong that aerosol characteristics (principally size distribution) in the Bay Area are different at night than in the day. With no photochemical source, higher relative humidity and less mixing, the size distribtuion tends to narrow to nearly monodisperse aerosol layers of size ($\sim$.5 μm). This is revealed by removing ozone, water, Rayleigh, and NO_2 extinction effects and seeing that the remaining aerosol extinction with wavelength often increases with increasing wavelength. This is a specific test for the size distribution referred to above and is rarely seen during the day. The second important result is that inversion strength and height are usually the dominant meteorological parameters related to atmospheric extinction. Small variations in the inversion height especially in poor visibility conditions make large differences in atmospheric transmission.

IN-SITU SPECTROPHONE MEASUREMENT FOR GASEOUS/PARTICULATE AEROSOLS

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Laser sources were applied to spectrophones about a decade ago. Some applications were reported in succeeding years, e.g., References 1-3, but their application to in-situ measurement of aerosols (atmospheric gases/particulates) is a recent phenomenon. There are two general types of systems; a static, twin chamber device in which a pressure rise proportional to the absorption coefficient is measured (Ref. 4). This type of system must be closed and thermally stabilized. It is subject to drift and is clearly not suited to flow-through use. The second chamber is to cancel the unwanted "window" signal.

The second general type uses a chopped or pulsed probe beam and an acoustic sensor in a generally resonant integral microphone system. A report on such applications is available (Ref. 5).

The first figure shows comparative ozone results (Ref. 6) using a chopped c-w source system. The next figure shows an application of a pulsed source system to another atmospheric gaseous absorber - at another wavelength region (Ref. 7).

The third figure shows the application of our basic technique, which involves acoustically isolated resonant subcavities (to effectively eliminate the window signals) operating in a differential mode to separately obtain atmospheric gaseous and particulate absorption values in situ, in flow through fashion. By grounding the filtered or the unfiltered units, all three (total, gaseous, particulate) quantities may be obtained (Ref. 8). Lab use of such a system is diagrammed in Figure 4 (Ref. 8).

Finally, in this brief vignette, such systems have been used for field measurements and much more compact units than that of Figure 4 are currently being tested.

Spectrophones do measure a quantity proportional to the absorption coefficient. This is significant when the components of the extinction, the scattering and absorption are needed (HE Laser, radiation budget, contrast modeling, albedo problems). The spectrophone is also linear with absorption coefficient over a number of decades while accuracy of a transmission measurement is quite limited in span. Absorption due to atmospheric particles is also measurable though care must be taken to consider the particle heating, cooling and flow problems when designing the system. It should also be noted that aerosol particle characterization is currently done primarily as a point measurement and may best be correlated with a point type propagation measurement.

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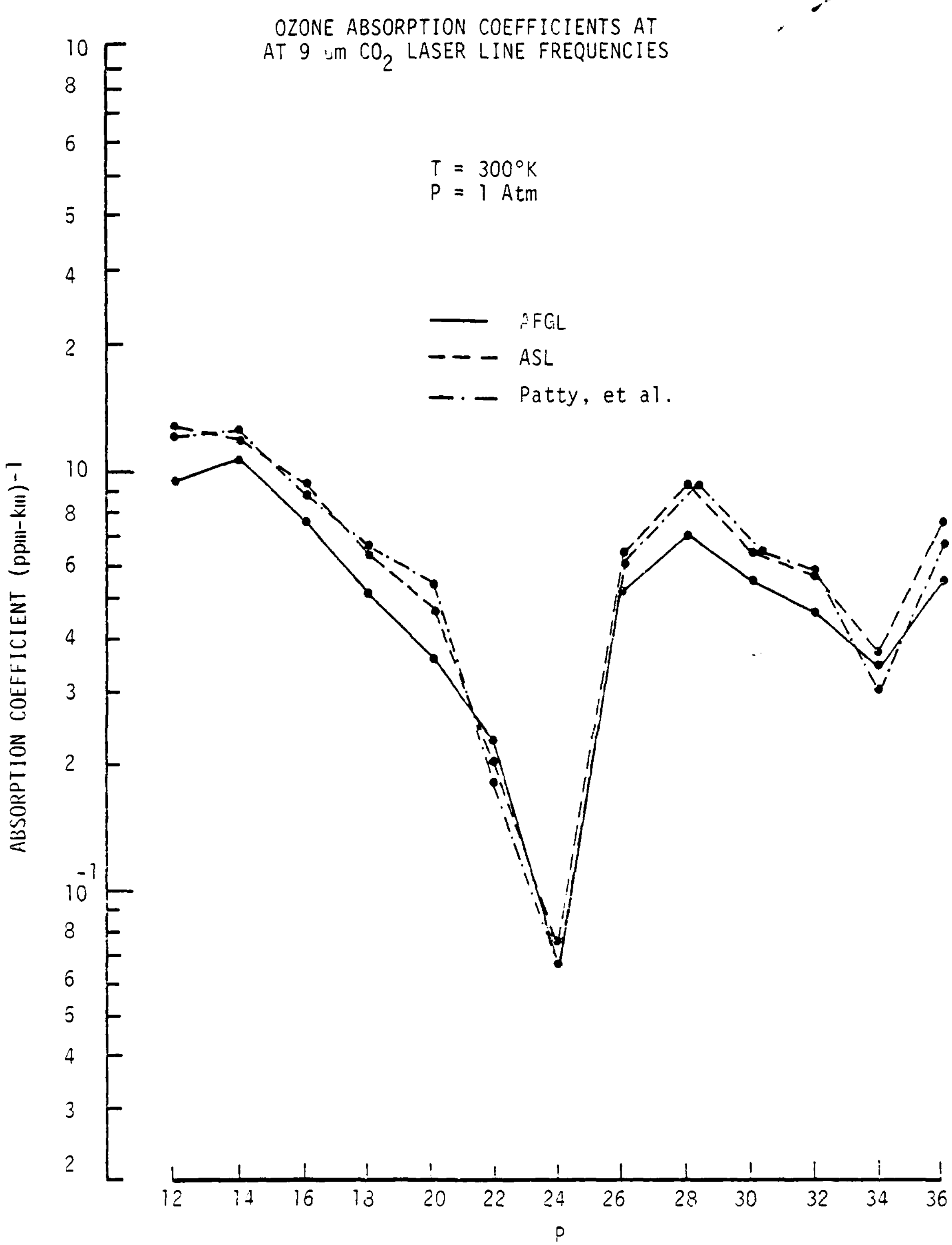

Figure 1. Pattern comparison for spectrophone and white cell absorption measurements. Ozone absorption coefficient is plotted vs laser line. The line connections between points are for visual ease of identification only.

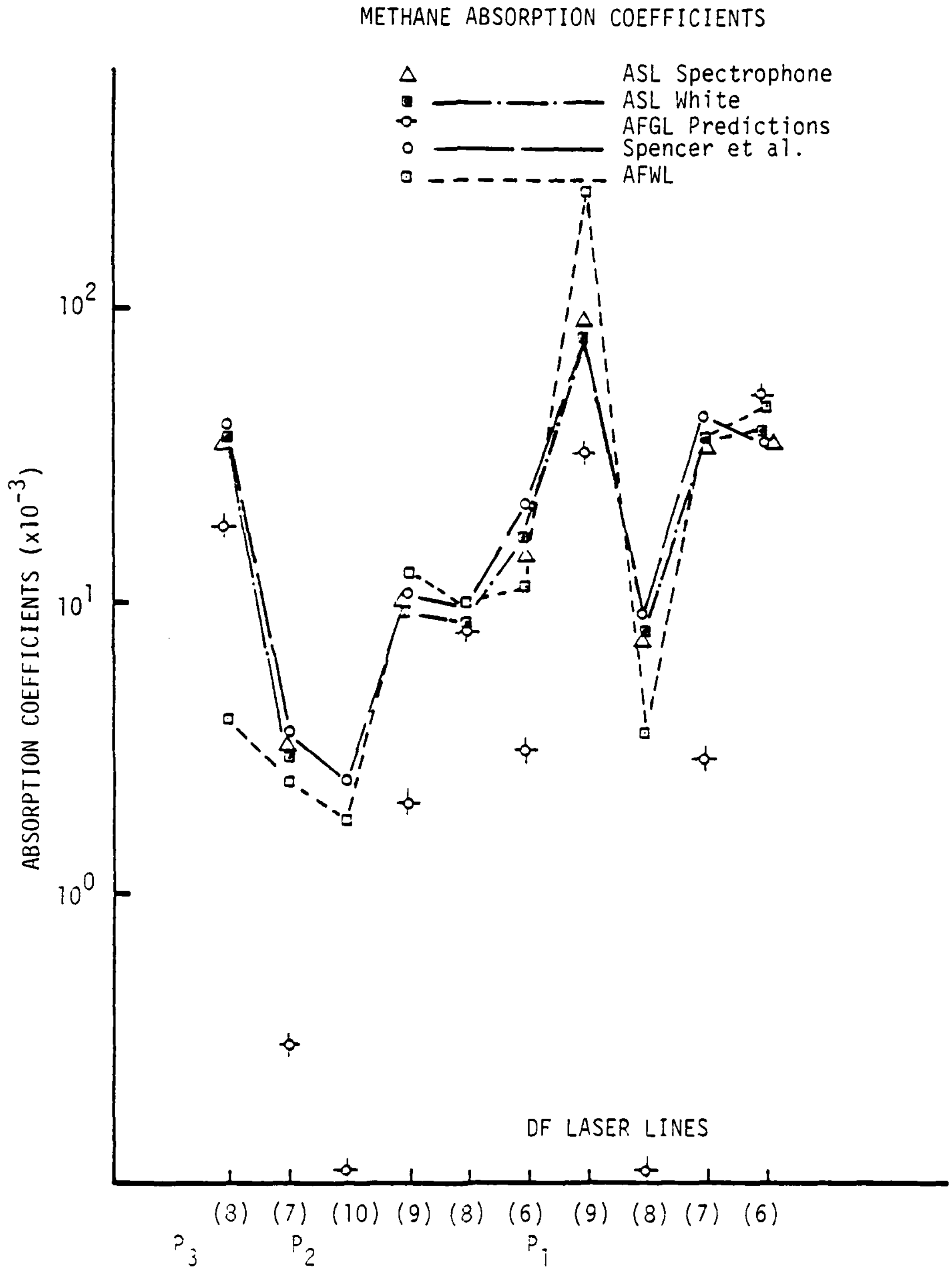

Figure 2. Comparative Spectrophone and White Cell Results. Methane Absorption Coefficients are Plotted for 9 DF Laser Wave-Lengths.

DIFFERENTIAL RESONANT SUBCHANGER FLOW-THROUGH SPECTROPHONE FOR GAS PARTICULATE ABSORPTION

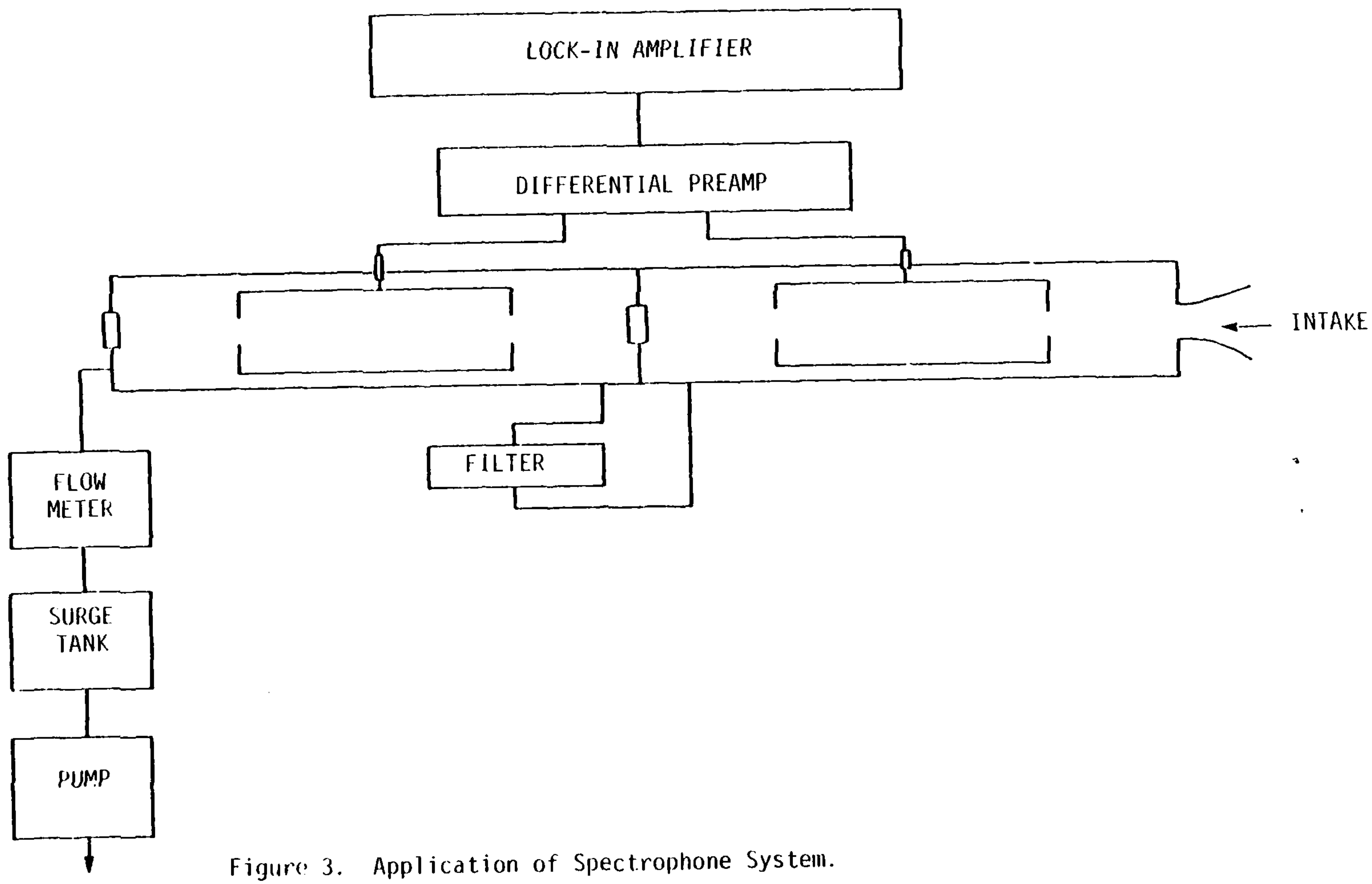

Figure 3. Application of Spectrophone System.

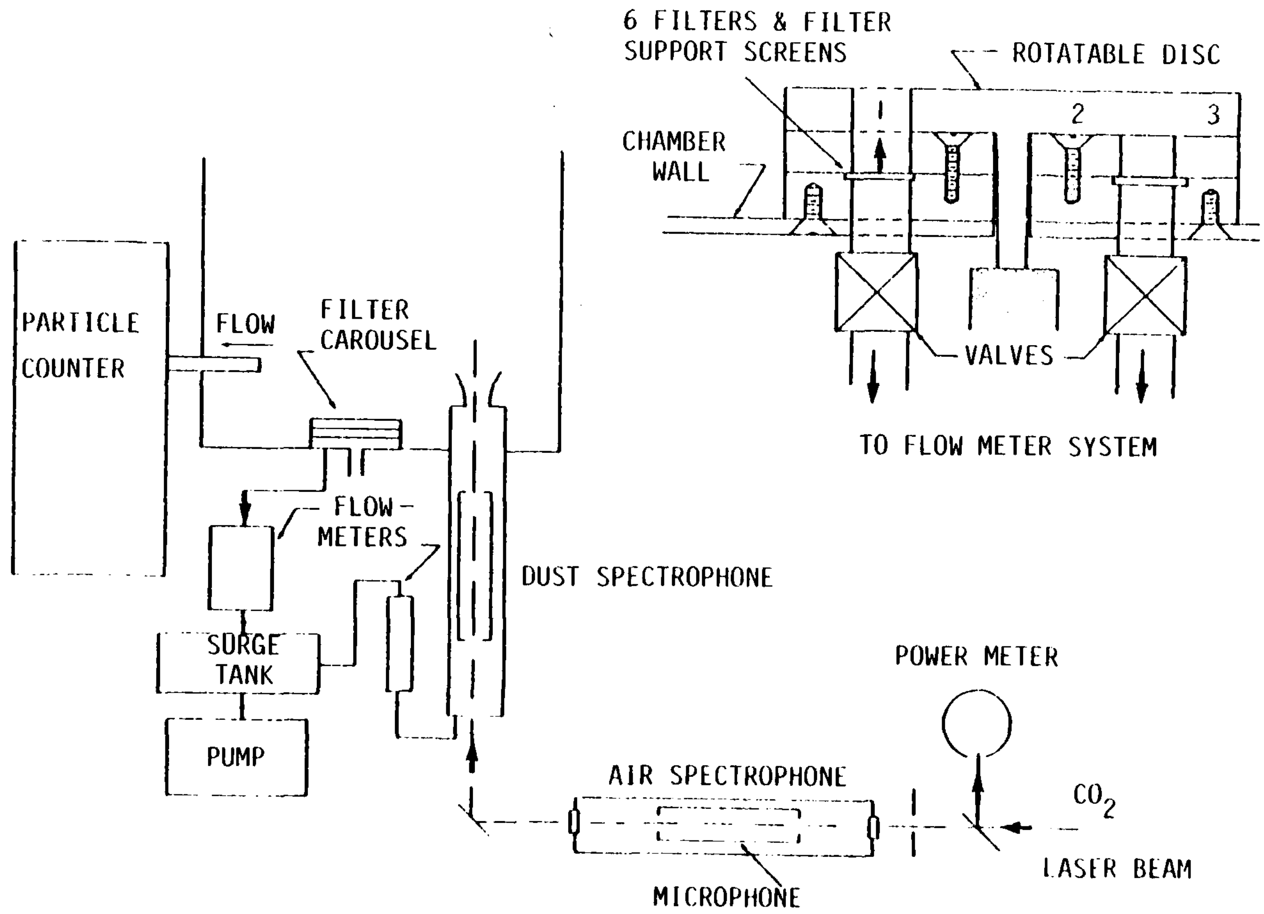

Figure 4. Laboratory Use of Spectrophone System.

A FEASIBILITY STUDY: APPLICATION OF LIDAR TRANSMISSION MEASUREMENT IN THE SLANT VISUAL RANGE PROBLEM

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The geometry, distances and transmission values to be measured which are applicable to transmission measurement in the slant visual range (SVR) problem were described (Figure 1). The required lack of any instrumentation or material at the airborne end of the visual path was emphasized.

The interpretation problem in attempting transmission measurements using lidar was introduced. Initial emphasis was put on the lidar equation, to see if workable techniques could be produced before looking at minimizing the effects of multiple scattering.

The possible use of lidar radiation scattered from the particles of the obscuring atmospheric dispersion was next discussed. An example of a technique which comes close in principle to making unambiguous transmission measurements under a variety of conditions was described followed by a discussion of the reason for the failure of this technique. The general problem occurring in utilizing scattering from the obscuring particles was presented in terms of an example. This was a plot of the attenuation coefficient for a homogeneous dispersion and the family of curves of attenuation coefficient versus range which give the same lidar return signal as the homogeneous dispersion regardless of the lidar used (Figure 2). Individual curves, though giving the same lidar signal, differ greatly in transmission through the dispersion. These curves were used to point out that even if the backscatter to attenuation coefficient ratio were constant with range, the very slight uncertainty in this ratio, in techniques which utilize its numerical value, will make any attempt to measure transmissions about and below 0.1 meaningless. (In addition, these curves give an indication that slight variations in this ratio will cause at least some techniques that rely on its being constant with range to fail in attempts to measure transmissions about and below 0.1). No sufficiently unambiguous technique which utilized scattering from the particles of the obscurant and which was applicable to the SVR problem could be devised or found.

For this reason use of the scattering from the atmospheric gas was investigated. A general technique was developed and presented which is free of ambiguity. A variation of this technique was discussed which promises reduced multiple scatter and T^2 problems due to reduced lidar beam path length, but substitutes other problems which appear to limit it to measurement of transmissions greater than 0.1.

The problem with these last techniques is the very weak signals involved due to the very weak scattering processes (molecular Rayleigh and Raman) which would have no chance whatsoever of detection save that frequency shifts occur.

Because of this a general approach was taken and those constraints were looked at which are imposed by nature, physics, eye safety, and SVR use in order to see what possibilities were allowed by these general constraints, constraints that any lidar system would have to satisfy.

It was found that eye safety alone set the optimum pulse repetition rate for laser scattering in the near UV and near IR, the regions of interest in the SVR problem. Using this optimum pulse repetition rate, maximum pulse and time averaged output energies were found. (Other curves are available including some weighted by wavelength to the inverse fourth power).

At present we are just concluding our study of the possibility of using Raman scattering. We are also considering Rayleigh scattering possibilities and the effects of multiple scattering via Eloranta and Shipley's small angle estimation technique.

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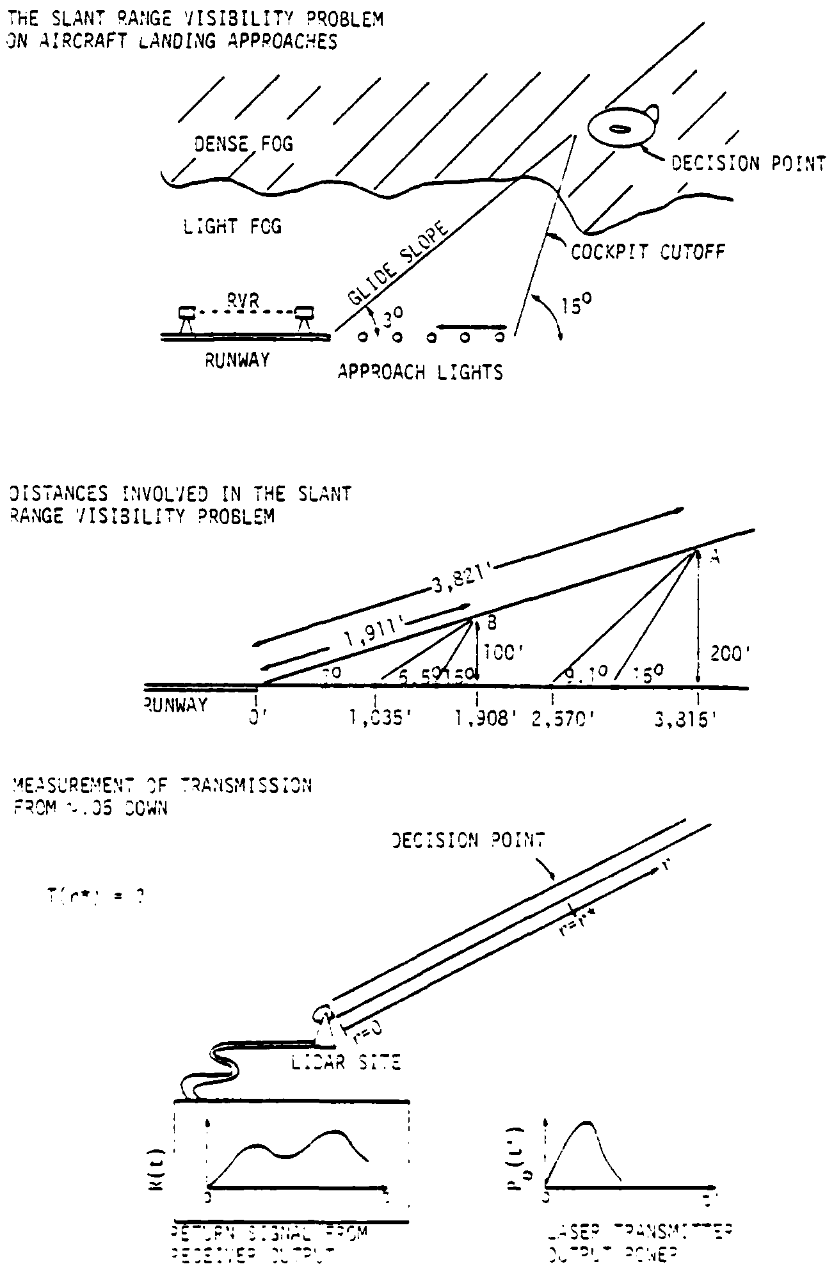

Figure 1. Geometry, Distances, and Transmission Values Involved in the SVR Problem.

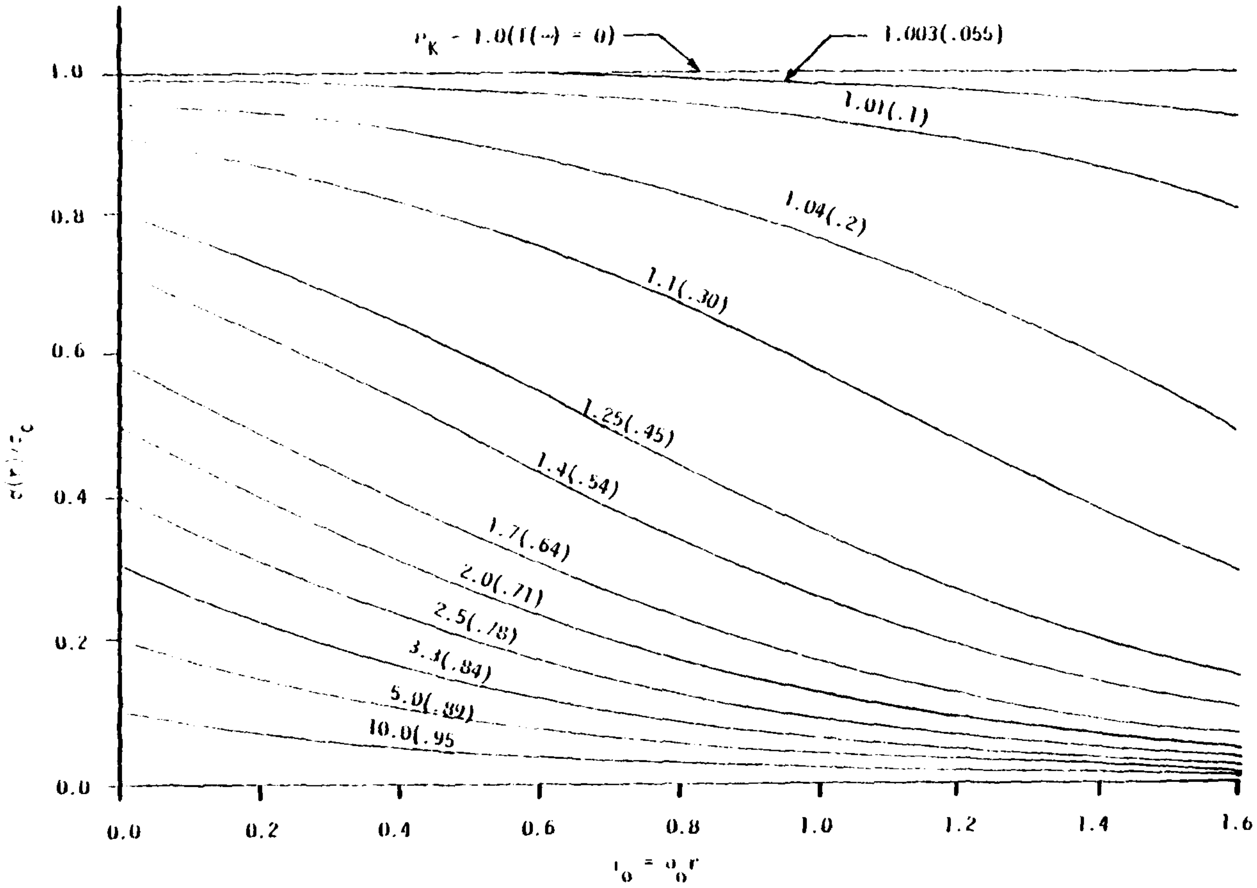

Figure 2. Family of Curves of Attenuation Coefficient Versus Range.

MULTIWAVELENGTH CONTRAST TELEPHOTOMETER

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The ability to see objects at a distance is affected by two mechanisms. First of all, light can be absorbed and/or scattered away from the path of vision by gas molecules and airborne particles. In addition, light is scattered by the atmosphere into the path of vision. Such light is often called glare, or atmospheric air light. Thus, a black object will increase in brightness from the air light and bright objects will be reduced in brightness by absorption and scattering.

The MRI VistaRanger* (manual or continuous) Telephotometer measures the light energy (or radiance) at four visible wavelengths of a target or sky. All measured values are relative to the standard light source used in the calibration. Then apparent target contrast, Cr, is defined to be:

$$Cr = \frac{N_c^t - N_c^s}{N_c^s}$$

where N_c^t and N_c^s are the target and sky radiance respectively, and c denotes the color of the light. In addition, values of N_{blue}, N_{green}, and N_{red} can be used to characterize color or color change. Measured radiance values, in the blue, green, and red portions of the spectrum, are combined mathematically to uniquely determine the color of a given target or sky. Color changes from one set of measurements to the next can also be calculated. Thus, the MRI VistaRanger measures parameters that relate directly to what an observer sees, namely: (1) apparent target contrast; and (2) apparent target color.

*The use of trade names in this report does not constitute an official endorsement or approval of the use of such commercial hardware or software. This report may not be cited for purpose of advertisement.

ATMOSPHERIC OPTICAL PARAMETERS

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There are two major problems with the measurement of atmospheric transmission. One is that the devices used are generally broad band and the transmission which is measured is dependent upon the response function of the instrument. This can be corrected by using narrow band devices or spectral instruments. The second problem is that photons which should be scattered out of a beam of radiation are sometimes scattered into the detector, resulting in an increase in the transmission over what it would be for a beam of infinitesimal width. A solution would be to use lasers with narrow beam widths or to model the scattering with wide beam sources.

For modern electro-optical military systems contrast and the spectral radiation field are of considerable importance and in some cases they are of greater importance than spectral transmittance. It is essential therefore, that one develop instrumentation to measure atmospheric optical parameters upon which contrast and radiation depend. A detailed description of many of these parameters and the relationship of one to another is provided in the figures.

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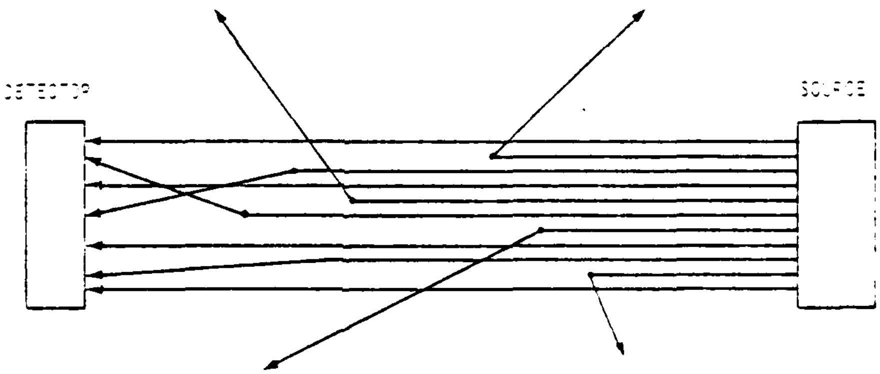
PROBLEM #1 WITH TRANSMISSOMETERS
(BROAD BAND)

$$\int_0^\infty E(\lambda,S)\phi(\lambda)d\lambda = \int_0^\infty E(\lambda,0)\phi(\lambda)T(\lambda,S)d\lambda$$

$$\int_0^\infty T(\lambda,S)d\lambda \neq \int_0^\infty E(\lambda,S)\phi(\lambda)d\lambda \Big/ \int_0^\infty E(\lambda,0)\phi(\lambda)d\lambda$$

$E(\lambda,S)$ - Spectral Power Density at Distance S,
$E(\lambda,0)$ - Spectral Power Density at Source, and
$\phi(\lambda)$ - Spectral Response Function of Instrument.

PROBLEM #2 WITH TRANSMISSOMETERS
(FINITE BEAM)

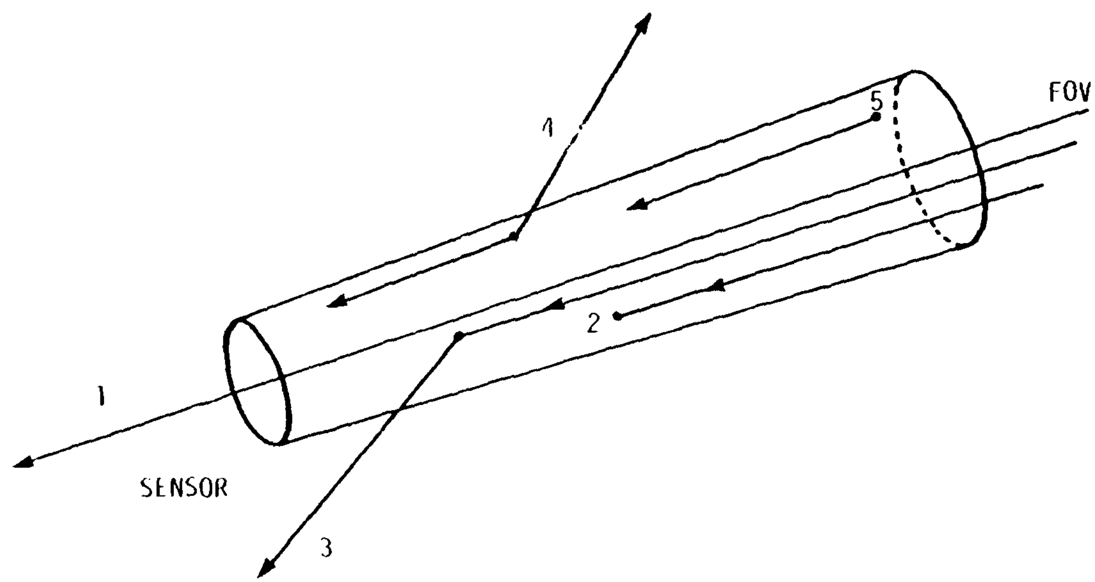


$E(\lambda,S)_{measured} = E(\lambda,0)T(\lambda,S)_{measured}$

$E(\lambda,S)_{actual} = E(\lambda,0)T(\lambda,S)_{actual}$

$T(\lambda,S)_{measured} > T(\lambda,S)_{actual}$

Figure 1. Major Problems with Transmissometry Measurements.



1. Non-Interacting Radiation (No Gain, No Loss)
2. Absorbed Radiation (Loss)
3. Scattered Radiation (Loss)
4. Scattered Radiation (Gain)
5. Emitted Radiation (Gain)

Figure 2. Interaction Mechanisms.

RADIATION COMPONENTS FOR SOURCE, TARGET, SENSOR GEOMETRY

$$L(s,\hat{\Omega}) = L_0(0,\hat{\Omega})T(s,\hat{\Omega}) + L_p(s,\hat{\Omega})$$

$L(s,\hat{\Omega})$ - radiance at sensor,
$L_0(0,\hat{\Omega})$ - radiance at target,
$T(s,\hat{\Omega})$ - transmittance between target and sensor, and
$L_p(s,\hat{\Omega})$ - path radiance.

TARGET RADIANCE

$$L_0(0,\hat{\Omega}) = \int \hat{n}\cdot\hat{\Omega}'\ \rho(\hat{\Omega},\hat{\Omega}') \left[L_{sun}(\hat{\Omega}') + L_{sky}(\hat{\Omega}') + L_{surf}(\hat{\Omega}')\right] d\hat{\Omega}' + L_{thermal}(\hat{\Omega})$$

$\rho(\hat{\Omega},\hat{\Omega}')$ - bi-directional reflectance of target, and
$\hat{n}$ - surface normal.

PATH RADIANCE

$$L_p(s,\hat{\Omega}) = L_{p,scatt}(s,\hat{\Omega}) + L_{p,emiss}(s,\hat{\Omega})$$

$L_{p,scatt}(s,\hat{\Omega})$ - radiance scattered into path, and
$L_{p,emiss}(s,\hat{\Omega})$ - radiance emitted along path.

Figure 3. Radiation Equations.

CONTRAST

$$C(\lambda,S) \equiv \frac{L_t(\lambda,S) - L_b(\lambda,S)}{L_b(\lambda,S)}$$

$$= C(\lambda,0)\,\frac{L_b(\lambda,0)}{L_b(\lambda,S)}\;T(\lambda,S)$$

$L_t(\lambda,S)$ - target radiance at distance S,
$L_b(\lambda,S)$ - background radiance at distance S,
$L_b(\lambda,0)$ - background radiance at target, and
$T(\lambda,S)$ - transmittance along distance S.

CONTRAST TRANSMITTANCE

$$T_c(\lambda,S) \equiv \frac{C(\lambda,S)}{C(\lambda,0)} = \frac{L_b(\lambda,0)}{L_b(\lambda,S)}\;T(\lambda,S)$$

$$= \frac{1}{1 + \dfrac{L_p(\lambda,S)}{L_b(\lambda,0)T(\lambda,S)}}$$

$L_p(\lambda,S)$ - path radiance.

Figure 4. Contrast Transmittance Equations.

$T(\lambda,S)$ - Spectral Transmittance Along Path S

$L_p(\lambda,S)$ - Spectral Radiance Along Path S

SPECTRAL TRANSMITTANCE

$$T(\lambda,S) = EXP\left[-\tau(\lambda,S)\right]$$

$$\tau(\lambda,S) = \int_0^S \left[k_g(\lambda,S') + k_a(\lambda,S')\right] dS'$$

$\tau(\lambda,S)$ - Optical Depth at Distance S

$k_g(\lambda,S)$ - Molecular Volume Extinction Coefficient

$k_a(\lambda,S)$ - Aerosol Volume Extinction Coefficient

AEROSOL DENSITIES

$$\rho(S) = N(S) \int_0^\infty n(r)m(r)dr$$

$\rho(S)$ - Aerosol Mass Density

$N(S)$ - Aerosol Number Density

$$M(S) = \int_0^S \rho(S') dS$$

$M(S)$ - Aerosol Column Density

MASS EXTINCTION COEFFICIENT

$$k_{a,m}(\lambda) = \frac{\int_0^\infty n(r)\sigma(\lambda,r)dr}{\int_0^\infty n(r)m(r)dr}$$

$m(r)$ - Mass of Particle of Size r

$k_{a,m}(\lambda)$ Is Independent of Number Density

VOLUME EXTINCTION COEFFICIENTS

$k_g(\lambda,S)$ - Depends Upon Gaseous Concentration

$$k_a(\lambda,S) = N(S) \int_0^\infty n(r)\sigma(\lambda,r)dr$$

$N(S)$ - Particulate Number Density

$n(r)$ - Particle Size Distribution

$\sigma(\lambda,r)$ - Particle Cross Section

Figure 5. Quantities of Major Importance in Electro-Optical Systems.

WHY MEASURE SOLAR IRRADIANCE?

SPECTRAL OPTICAL THICKNESS $\tau_0(\lambda)$ IS DETERMINED

$$\tau_0(\lambda) = \cos \theta_0 \ln \left[\frac{E_0(\lambda)}{E(\lambda)}\right]$$

θ_0 - solar zenith angle,

$E_0(\lambda)$ - extra terrestrial solar irradiance, and

$E(\lambda)$ - solar irradiance at radiometer.

RADIOMETER REQUIREMENTS

1. Variable Field of View ($\theta \geq 0.5$ Degrees)
2. Wavelength Bands: 380-400 NM, 420-440 NM, 450-470 NM, 510-530 NM, 540-560 NM, 580-600 NM, 620-640 NM, 660-680 NM, 700-720 NM, 730-750 NM, 830-850 NM, 930-950 NM, 3 - 5 μM (spectral), 8 - 12 μM (spectral)
3. Accurate Clock Drive
4. Rugged, Physically Stable for Field Operations

Figure 6. Solar Irradiance Considerations.

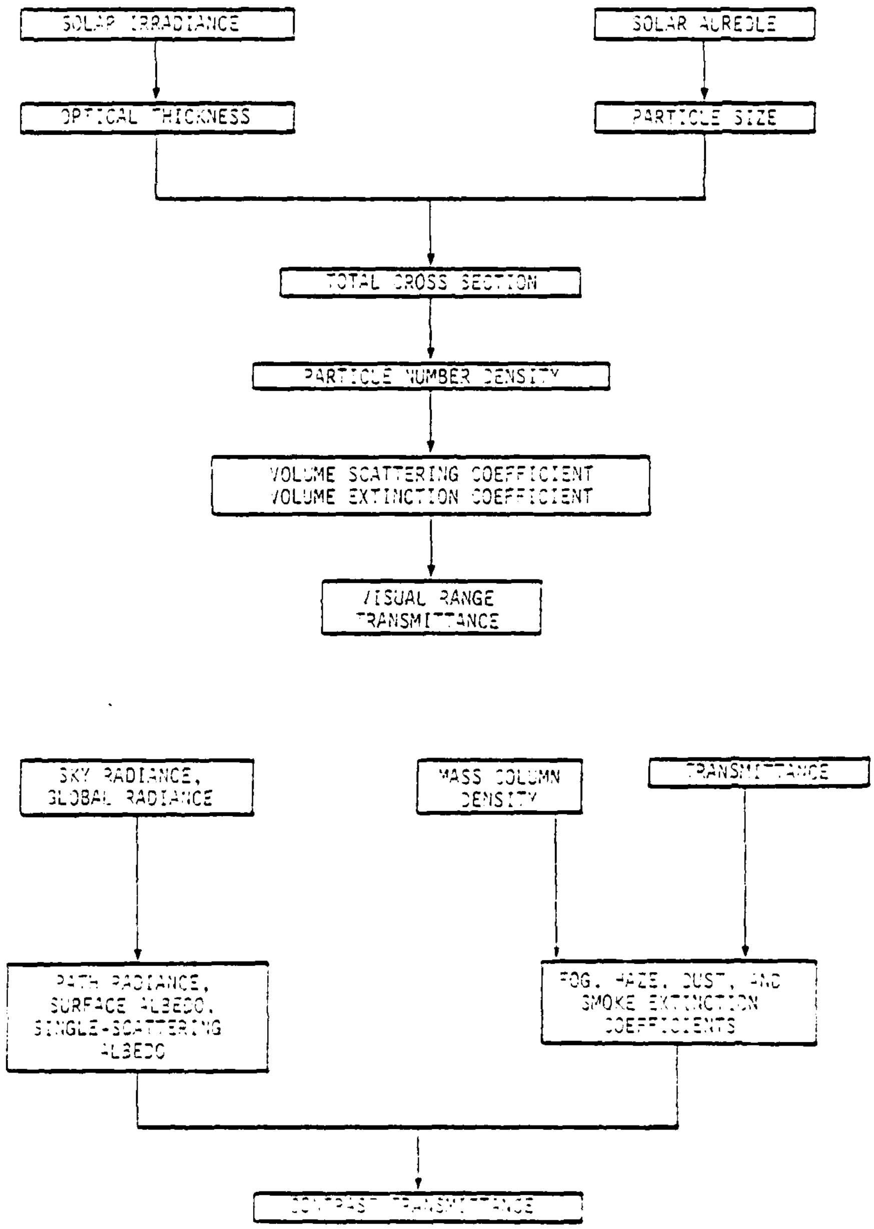


Figure 7. Contrast Transmittance Model.

INSTRUMENTATION IS NEEDED TO MEASURE
THE ATMOSPHERIC OPTICAL QUANTITIES ...

1. Solar (Lunar) Radiance
2. Solar Aureole
3. Sky (Diffuse) Radiance
4. Global (Sky Plus Solar) Irradiance
5. Spectral Transmittance (Visible Region)
6. Spectral Transmittance (Thermal Infrared)
7. Aerosol Mass Density (GMS/CM^3)
8. Aerosol Column Density (GMS/CM^2)

NEEDED: Calibrated, Visible And Near IR Spectro-Radiometers With Accurate Clock Drive And Variable Field of View.

NEEDED: Calibrated Thermal Infrared And Visible Narrow Band Transmissometers With Variable Beam Width.

NEEDED: Instrument For The Remote Measurement Of the Particulate Mass Column Density.

NEEDED: Instrument To Measure Liquid Water Content.

Figure 8. Conclusions.

DETERMINING REFRACTIVE INDEX STRUCTURE CONSTANT BY THE SCINTILLATION METHOD

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An important property of the air along an optical path is that of the refractive-index structure or C_n^2. The effect of high values of C_n^2 is to degrade the resolution of an imaging optical system.

The scintillation of an incoherent light source viewed through the atmosphere is an indication of the optical (thermal) turbulence in the medium. The twinkling of a star is the most familiar example of this kind of scintillation. In scintillation type C_n^2 detectors, a light source is directed at a receiver placed some distance away. The receiver consists of a collecting objective focused upon a photo diode. As the atmosphere between the light source and the receiver becomes more turbulent, fluctuations appear in the output of the photo diode. The amplitude of the fluctuations is a measure of the difference in index of refraction of cells which traverse the line of sight. By measuring the log intensity variation, a determination of average C_n^2 along the path can be made.

A drawback to this method is the occurrence of saturation (for simplistic receivers) as frequency and intensity of the fluctuations become large: photo diode output remains relatively constant with further increases in C_n^2.

To decrease this saturation effect, a dual aperture receiver can be utilized in which two objectives with separate detectors placed side-by-side are compared. The outputs are subtracted in a differential amplifier. This difference signal is less prone to saturate with large values of C_n^2. The spacing between the apertures is chosen large enough so that a majority of cells which produce the scintillation phenomenon are uncorrelated between the two apertures.

Basing equipment design (including the dual aperture technique) on previous research done at the National Oceanic and Atmospheric Administration, Lockheed (Huntsville Research and Engineering Center) has developed a C_n^2 detector suitable for the particular requirements of the Army Test and Evaluation Directorate at Redstone Arsenal.

When such a C_n^2 receiver and its light source have been installed at the desired site, one can relate the processor output voltages to C_n^2 through a simple calibration procedure. The processor has a switch selectable "calibration mode." When the processor is operated in this "calibration mode," the amplifiers are DC coupled, bypassing the filter stage. Calibration consists of setting a single adjustment to establish the overall gain of the amplifier in the processor. To determine the appropriate setting, the system is operated at night to reduce background illumination. The lamp is turned "on" then "off" and the difference in processor output voltage level represents $\overline{V}_m$ in the following equation,

$$C_n^2 = 5.16 \times 10^{-6} \frac{V^2}{L^3 V_m^2}$$

where V is the processor output voltage and L is the distance in meters between the lamp and receiver.

The above procedure will calibrate the unit for a set of conditions where the transmission along the path is equal to that during calibration. Obscurants which are interposed between the receiver and light source alter calibration.

In the Redstone application, three Lockheed systems each with a range of 800 meters are placed end to end along a North-South line to monitor C_n^2 approximately two meters above the ground along a line 2400 meters in length. In addition, at a point approximately 800 meters from the North end, four receivers are operated over a short East-West line at heights above the ground from two meters to sixteen meters. The outputs of the processor are sampled twenty times per second by a Hewlett-Packard 1000 computer. Calculations of C_n^2 are based upon one-second averages of the processor outputs and logged on magnetic tape.

The data obtained from this type of C_n^2 detection system is the weighted average of C_n^2 over the path. The weighting constant is unity in the center and near zero on both ends. According to theory, the weighting function can be shifted toward the receiver or toward the light source from the center by choosing different apertures for light source and receiver.

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APPENDIX B

PARTICLE SIZE MEASUREMENT PAPERS

THE EFFECT OF ATMOSPHERIC AEROSOLS
ON EO SYSTEM PERFORMANCE

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INTRODUCTION

In reviewing the effects of atmospheric aerosols on the performance of electro-optical systems, preliminary discussion will focus on the parameters which affect the optical properties of the atmosphere, and how these parameters fold into the overall determination of system performance. Next, the effects of atmospheric aerosols on electro-optical system performance including the detection of incoherent radiation sources, as well as the propagation and detection of laser radiation will be given. Finally, the manner in which the optical properties of the atmosphere are measured will be discussed and reference made to a recent series of aerosol measurements on San Nicolas Island.

ATMOSPHERIC OPTICAL PROPERTIES

The optical properties of the atmosphere are determined by the combined effects of molecular absorption and scattering, as well as aerosol absorption and scattering. While aerosols are the primary subject of this meeting, the effects of molecular absorption and scattering cannot be ignored in determining atmospheric optical properties. Typical atmospheric aerosol particle size distributions are shown in Figure 1 for continental, maritime and fog type atmospheres. These particle size distributions have decidedly different shapes and magnitudes. The ordinate in Figure 1 represents the particles per cubic centimeter per micron increment of particle radius. The abscissa represents the radii of the particles in units of microns. If Mie scattering calculations are carried out for these typical particle size distributions at .9 and 10.6 microns wavelength, angular scattering functions such as those shown in Figures 2 and 3 are obtained. The angular scattering distributions, or single scattering phase functions, represent the fraction of radiation scattered from the beam per unit length per steradian as a function of the scattering angle. As can be seen from Figures 2 and 3, the scattering properties of these various aerosol types differ markedly from each other. If the angular scattering functions are integrated for all scattering angles, the scattering coefficient $k_{SCATT,A}$ can be determined. The intensity of radiation within the beam will attenuate exponentially with this scattering coefficient.

The relationship between the basic atmospheric constituents, atmospheric optical properties and the atmospheric propagation models used to predict the energy incident on receiver apertures is shown in Figure 4. As can be seen, the concentration of molecular absorbers, the concentration and composition of molecular scatterers, and the concentration, composition, and size distribution of atmospheric aerosols lead directly to the exponential absorption and scattering coefficients. The absolute value of the single scattering

phase function is also determined by summing the aerosol and molecular components. The sum of all the exponential coefficients is known as the attenuation or extinction coefficient which represents the exponential decay of energy within a beam due to both scattering and absorption. These atmospheric optical properties are required inputs of all atmospheric propagation models. Atmospheric propagation models range from very simple single scatter models to more complex forward scatter models and very complex solutions of the radiative transfer equation including multiple recursion formulas and Monte Carlo techniques. The end result of these atmospheric propagation models is the determination of the total energy incident on the receiver aperture, including the angular and temporal distributions, as well as statistical fluctuations.

The optical properties of the atmosphere are primary factors controlling the response of many electro-optical systems. As an example, the factors affecting the response of infrared missile warning receivers are shown schematically in Figure 5. In order to predict the response of a particular warning receiver, it is necessary to specify the generally time varying missile to receiver geometry, including the height of both the missile and receiver above the ground and the angular orientation in space of both the plume axis of symmetry and the receiver optical axis. The missile plume radiation charteristics must be specified as a function of time, wavelength, and aspect angle with which the missile is viewed. Likewise, the sensitivity of the warning depends on both wavelength and angle from the detector optical axis. The atmospheric optical properties which affect warning receiver response are the scattering and absorption coefficients of both aerosol and molecular species, and the angular distribution of the scattered radiation. Note that the nomenclature used for the atmospheric optical properties in Figure 5 differs slightly from that used in Figure 4.

The angular scattering distribution, or single scattering phase function, can be measured using a scanning polar nephelometer. Scattering from a parallel beam of incident radiation is detected with a narrow field-of-view detector for various scattering angles. Typical results of such an experiment in the ultraviolet portion of the spectrum are shown in Figure 6 which represents data measured in Princeton, New Jersey in December of 1977 and again in January of 1978. As can be seen, the scattering coefficient on the 1st of December was more than ten times greater than that measured on the 19th of January. It is also interesting to note that the scattering at scattering angles below 10° differed by several orders of magnitude from one day to the other. This high sensitivity of low angle scattering to ambient aerosols is extremely important in the performance of some electro-optical systems. The theoretical solid line in Figure 6 was determined from measured aerosol particle size distributions together with Mie and Rayleigh scattering theory.

Strong variations in aerosol scattering are also observed with time of day and with altitude above the ground. Figure 7 shows a typical variation of the exponential coefficients as a function of time of day, while Figure 8 shows a typical variation of the coefficients with altitude above the ground. It is apparent from Figures 6, 7, and 8 that the documentation of atmospheric optical properties is not an easy task.

EFFECTS OF AEROSOLS ON ELECTRO-OPTICAL SYSTEMS

It has long been recognized that atmospheric aerosols can have a detrimental effect on the performance of narrow field-of-view detectors which are looking for point sources of radiation through the atmosphere. These narrow field-of-view detectors such as reticle seekers, televisions, FLIRS, telescopes, and infrared warning receivers suffer a general degradation in performance due to the attenuation or extinction of the radiation between the point source and the detector. These types of systems are typically background limited which is the primary reason for the narrow field-of-view. More recently, wide field-of-view detectors have become available for scenarios in which background radiation is not the limiting factor. These wide field-of-view detectors respond not only to directly transmitted radiation between the source and detector, but also to scattered radiation from the source.

An example of the combined effects of absorption and scattering on wide field-of-view detectors is shown in Figure 9 which is the result of a parametric investigation into the effect of receiver field-of-view angle on the radiation received from a point source at a wavelength of 265 nanometers. Nine different weather conditions were chosen for this investigation including all combinations of high, medium and low scattering together with high, medium and low absorption. The relative degrees of absorption and scattering are shown in parentheses. As can be seen from Figure 9 when the field-of-view angle is increased about the source to receiver line-of-site, the total amount of radiation received increased significantly due to the scattered contribution. The smallest total signals are received for low scattering and high absorption while the highest signals are received for high scattering and low absorption. The manner in which the total received energy varies as a function of range for a wide field-of-view ($\theta = 45°$) system is shown in Figure 10. As can be seen, the received energy at a range of 6 kilometers varies by more than three orders of magnitude. In general, the effects of molecular absorption outweigh the effects of aerosol scattering at long ranges.

In sharp contrast to the detection of radiation from a point source described above, the detection of radiation from laser beams is enhanced by aerosols. In the coming years, strategic and tactical lasers will proliferate in the battlefield. Warning receivers designed to detect laser radiation work primarily in the aerosol scattering mode. Due to small beam divergences, it is unlikely that laser radiation will strike the warning receivers directly. In many cases, it is absolutely necessary that the warning receiver detect the presence of the laser radiation prior to a direct illumination. Since laser warning receivers are designed primarily to detect laser beams at laser miss angles of less than 5°, the response of the warning receivers can vary by orders of magnitude depending on the prevailing aerosol size distribution. Figure 6, for example, showed a nearly three order of magnitude difference in the aerosol scattering inside of 10° for two different days in the same geographic location. Thus, the performance of an electro-optical system designed to detect laser radiation is driven strongly by the prevailing weather conditions. The laser beam itself is attenuated by aerosol scattering, so that the performance of the laser system is degraded by atmospheric aerosols while the performance of the laser warning receiver is enhanced.

An example of the sensitivity of laser scattering radiation to laser miss angle is shown in Figures 11 and 12. Figure 11 shows an experimental set-up in which a laser beam is parametrically fired at various elevations above a detector. Likewise, the detector is rotated to various elevation angles above the laser. Measured values of the laser scattering as well as theoretical values, predicted from an atmospheric propagation model and aerosol particle size measurements, are shown in Figure 12.

DESIGN. TEST AND OPERATION

The manner in which atmospheric aerosols affect the performance of electro-optical systems should be taken into account early in the design phase. Parametric analyses should be carried out to determine the degradation or enhancement of system performance which could reasonably be expected in various geographic locations and various weather conditions. These parametric investigations may be largely analytical if the analytical models used have been verified with experimental data. It is especially important that the analytical models used represent such real world effects as absorbing ground planes, vertical aerosol gradients, reflecting clouds and a completely general source and receiver geometry.

In the testing and evaluation of breadboard, brassboard and prototype electro-optical systems, it is necessary that the effects of the atmospheric aerosols on the system performance be clearly understood. Since test programs of this type are extremely expensive, it is not possible to test the systems in all weather conditions and all geographic locations. It is, therefore, necessary to extrapolate the performance of these systems via validated models to other weather conditions and other geographic locations. In many cases, test and evaluation programs are not sufficient in extent to include these necessary mathematical extrapolations. Therefore, it is very important that, as a minimum, the atmospheric optical properties existing at the time of the test and evaluation be carefully measured and documented. It is also important that experienced analytical modelers participate in the planning of the test and evaluation programs to assure that all parameters required for future modeling and extrapolations are accounted for.

Once a production model of the electro-optical system is in the field, it may be necessary to have knowledge of the prevailing atmospheric optical properties in order to adjust certain settings or interpret the response of the system. Determining the atmospheric optical properties in an operational environment is an entirely different problem than during the test and evaluation program. During test and evaluation programs, experienced scientists and large amounts of equipment can be located on-site for extensive, well documented and expensive measurements. In the operational use of the electro-optical systems, either an extremely inexpensive and simple device must be used, or an eyeball estimate of prevailing visibility, temperature, etc., must be used to gauge these atmospheric optical properties.

Two approaches to this problem are currently being discussed in the aerosol measurement community. One approach is to develop models to predict the atmospheric optical properties with very simple input such as visibility, temperature, surface temperature, humidity and pressure. These models would

be developed through extensive experimental and theoretical research programs involving sophisticated instrumentation and computer models. The other approach is to develop very simple instruments which could be used in the operational scenario by semi-skilled personnel to directly measure the atmospheric optical properties. Whichever approach is to be taken, it is certain that some interaction will be required between future electro-optical systems and the prevailing atmospheric conditions.

DIRECT MEASUREMENT OF BULK OPTICAL PROPERTIES VS. PARTICLE SIZE MEASUREMENTS

It is important to realize that atmospheric aerosols are generally composed of both solid and liquid phase matter. Some devices for measuring aerosol concentration or aerosol size distributions are applicable only to dry aerosols and are, therefore, of limited value in making size measurements relevant to atmospheric optical properties. Several techniques do exist for measuring the particle size distributions of two phase aerosols using techniques such as light scattering and electronic mobility. Some aerosol measuring devices use Mie scattering theory in reverse to convert scattered radiation into particle sizes. In this case, Mie scattering theory is used to extrapolate the optical properties from perhaps a single wavelength and a narrow range of scattering angles into other wavelength regions and other scattering angles.

Before proceeding on, we should distinguish between remote and point measurements of aerosols or bulk optical properties. Single ended remote measurements are typically accomplished with lidar techniques in which reflected energy from laser pulses is used to infer atmospheric optical properties or particle size distributions. Double ended remote measurements of either extinction or scattering can also be used to determine atmospheric optical properties with some spatial resolution. Remote measurements generally suffer from either the inconvenience of performing double ended measurements or the lack of information content available in a single ended measurement. Point measurements of aerosol size distributions are typically made with sampling type aerosol analyzers, while bulk optical properties are measured via integrating or polar nephelometers. The single scattering phase functions shown in earlier figures are measured with scanning polar nephelometers. Point measurements have the advantages of both high information content and the convenience of single ended measurements. Point measurements have the disadvantage of representing only a single point which may be uncharacteristic of other spatial locations along the path.

The direct measurement of bulk optical properties using polar nephelometers or double ended extinction and scattering measurements can generally be accomplished with a greater degree of experimental accuracy than the prediction of these optical properties from measured particle size distributions and Mie scattering theory. However, the ease and accuracy with which these directly measured bulk optical properties can be extrapolated to other wavelengths is not clear. It may, in fact, be necessary to use Mie scattering theory together with these bulk optical measurements to infer a particle size distribution which can then be used to predict the optical properties at other wavelengths. Whether particle size measurements or

directly measured bulk optical properties are used, extrapolation to other wavelengths requires knowledge of the refractive indices at those wavelengths which are generally unknown. Multi-wavelength scanning polar nephelometers provide some indication of the trend in these refractive indices as a function of wavelength.

Recently, an electro-optical instrumentation workshop was held at the Wave Propagation Laboratory of NOAA in Boulder, Colorado. The purpose of the workshop was to discuss instrumentation needs in the aerosol/atmospheric optical properties area. Immediately prior to this workshop, a meeting was held to discuss the results of a Knollenberg spectrometer experiment which was carried out on San Nicolas Island in May of 1979. In the San Nicolas Island experiments, eleven Knollenberg particle measuring system aerosol size analyzers were placed side by side for a two week period. Bulk optical properties were measured simultaneously to these particle size measurements. Without going into great detail, the results of this investigation showed that the atmospheric scattering coefficients predicted from these particle size distributions using Mie scattering theory varied by a factor of three among the various instruments. Figure 13 shows predicted values of the aerosol scattering coefficient from these various instruments as a function of time of day. As can be seen, a factor of approximately three differences exists between the lowest and the highest values of atmospheric extinction coefficient inferred from the particle size measurements. In light of the fact that these errors in the scattering coefficient will amplify exponentially in the determination of path attenuation, it is clear that the state-of-the-art in the determination of atmospheric optical properties needs to be improved.

CONCLUSIONS

Atmospheric aerosols affect the performance of various electro-optical systems differently. Small field-of-view receivers observing point sources of radiation generally suffer attenuation due to atmospheric aerosols. Wide field-of-view systems can be used to recover at least a portion of this lost radiation due to atmospheric scattering. Atmospheric aerosols enhance the detection of off-axis laser scattered radiation, as well as the performance of non-line-of-site systems such as an ultraviolet voice communication system. In order to predict the effects of atmospheric aerosols on electro-optical system performance, it is necessary to know the bulk optical properties of the atmosphere, including the scattering and absorption coefficients due to both molecular and aerosol species, as well as the angular scattering distribution.

For many applications, the angular scattering distribution or single scattering phase function is critical, especially for off-axis detection of laser radiation. The detection of laser radiation for miss angles of less than 5 degrees is important for most laser warning receiver designs. Theory and experiment alike show that aerosol scattering at scattering angles of less than 5 degrees can vary by several orders of magnitude from one day to the next and from one geographic location to the next. Thus, the performance of these systems is driven by the prevailing atmospheric conditions.

Errors in the measurements of bulk optical properties are amplified exponentially in the prediction of system performance. The state-of-the-art in aerosol particle size measurements leaves a factor of three doubt as to the value of the aerosol scattering coefficient and, therefore, improvements in measurement techniques need to be made. Direct measurement of bulk optical properties offers some promise in this regard since they can generally be measured with a higher degree of experimental accuracy.

The effects of atmospheric aerosols are crucial in the design, testing and operation of electro-optical systems. Parametric analyses must be carried out in the early design phases of electro-optical systems. Likewise, at the time of testing and evaluation of these systems, it is important that the atmospheric optical properties be accurately measured and documented so that the results can later be extrapolated to other weather conditions and other geographic locations. Once production models of these electro-optical systems are in operation, it may be necessary to make adjustments in the instrument settings or interpret the results based on the prevailing atmospheric optical properties. Simple and inexpensive means must be developed for determining atmospheric optical properties in the operational scenario.

Measurements of particle size distribution appear to be more technologically difficult than direct measurements of bulk optical properties. However, the extrapolation of the results of these directly measured optical properties to other wavelengths needs to be investigated more thoroughly. Whether aerosol particle sizes or direct measurements are used to determine bulk optical properties, extrapolations to other wavelengths require knowledge of the wavelength dependent refractive indices which generally are not available.

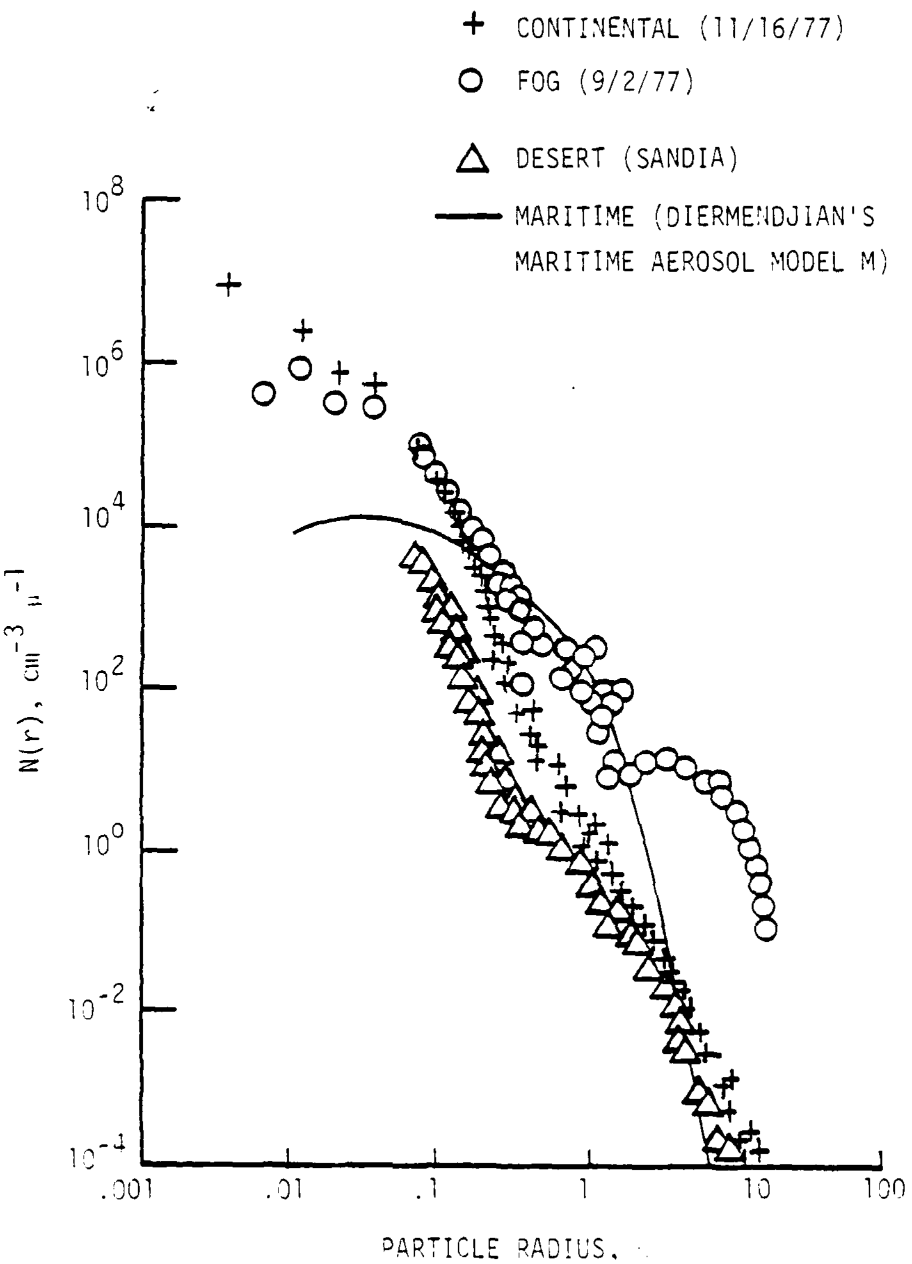


Figure 1. Typical Aerosol Particulate Size Distributions.

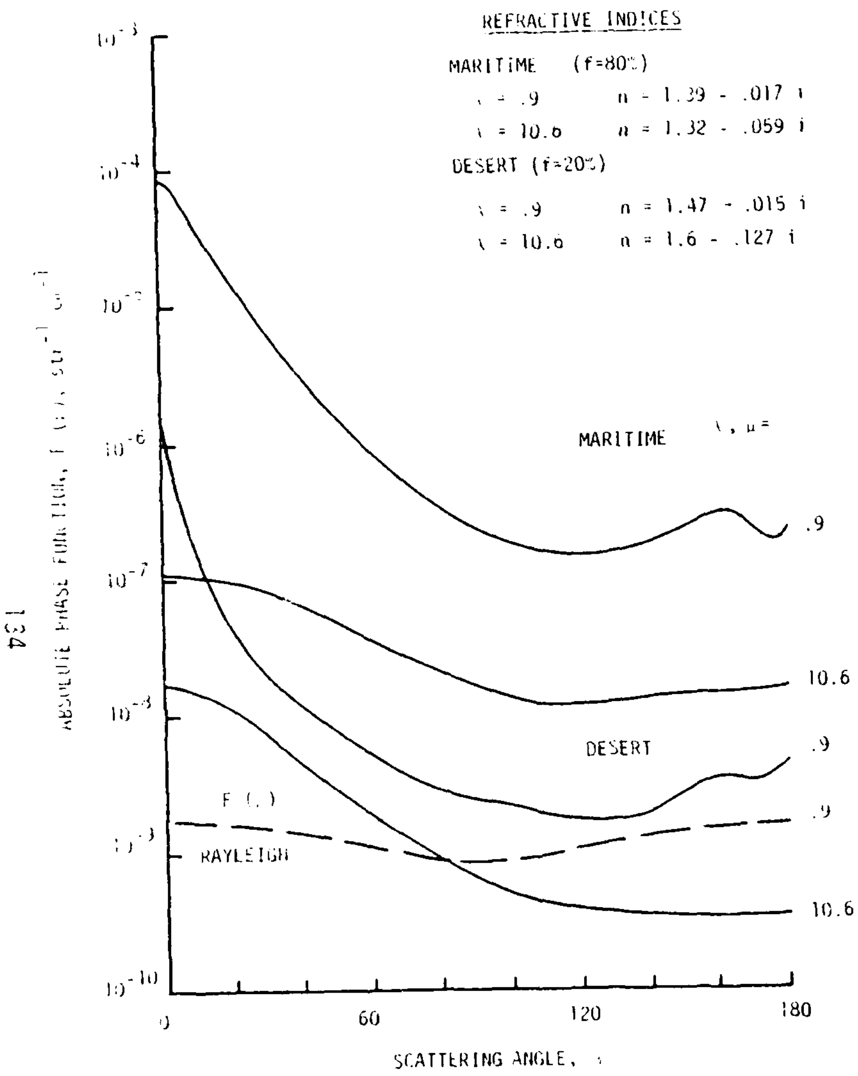


Figure 2. Angular Scattering Functions from Mie Calculations at .9 and 10.6 μm.

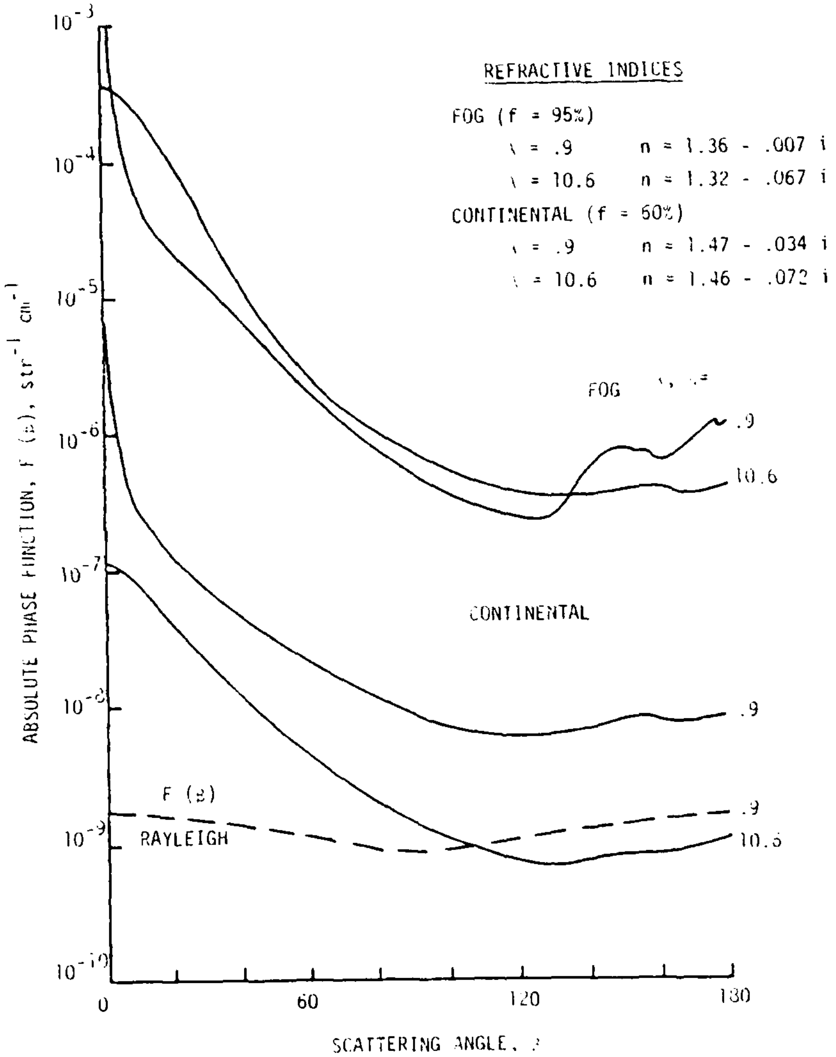


Figure 3. Angular Scattering Functions from Mie Calculations at .9 and 10.6 μm.

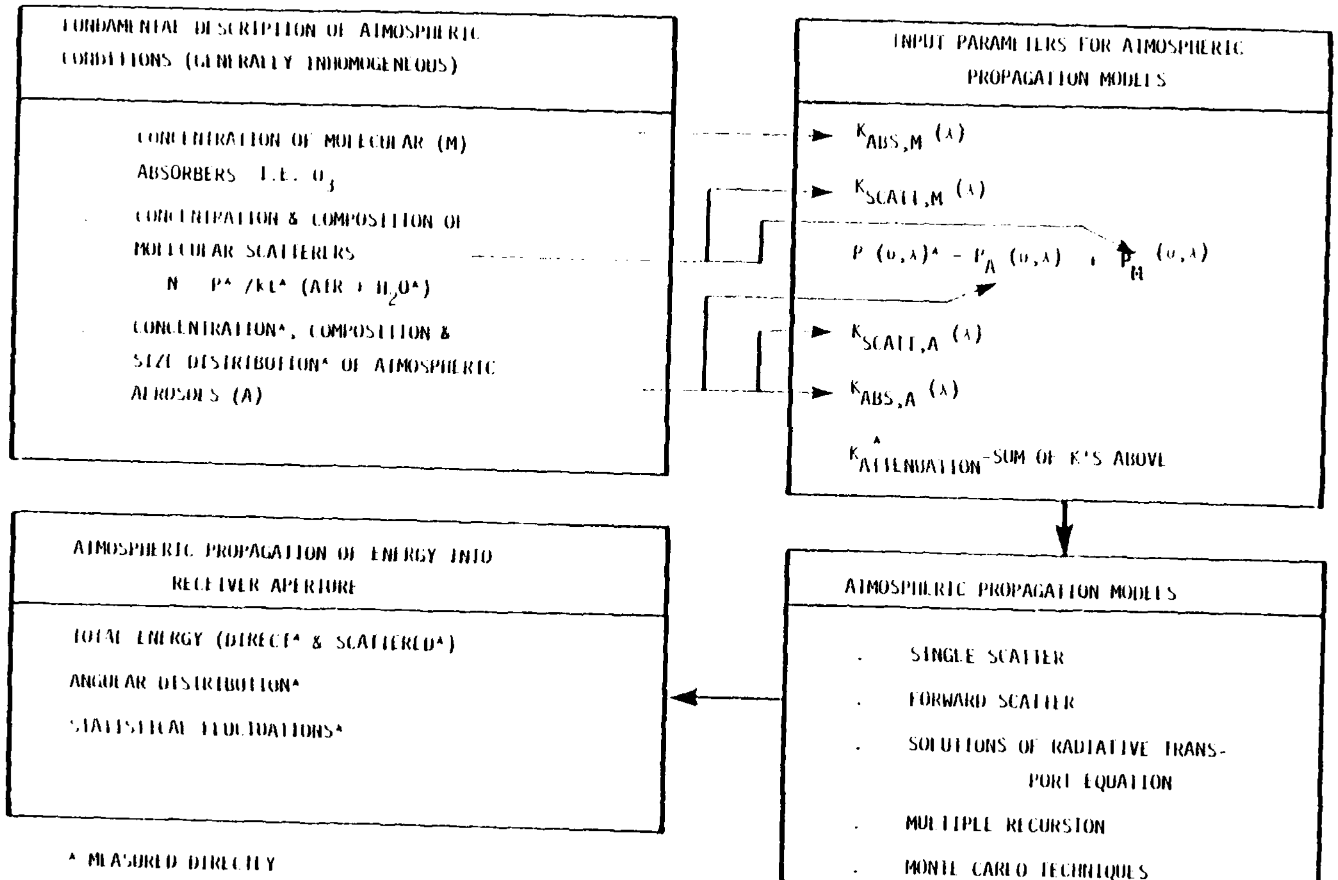


Figure 4. Atmospheric Propagation: Fundamental Approach.

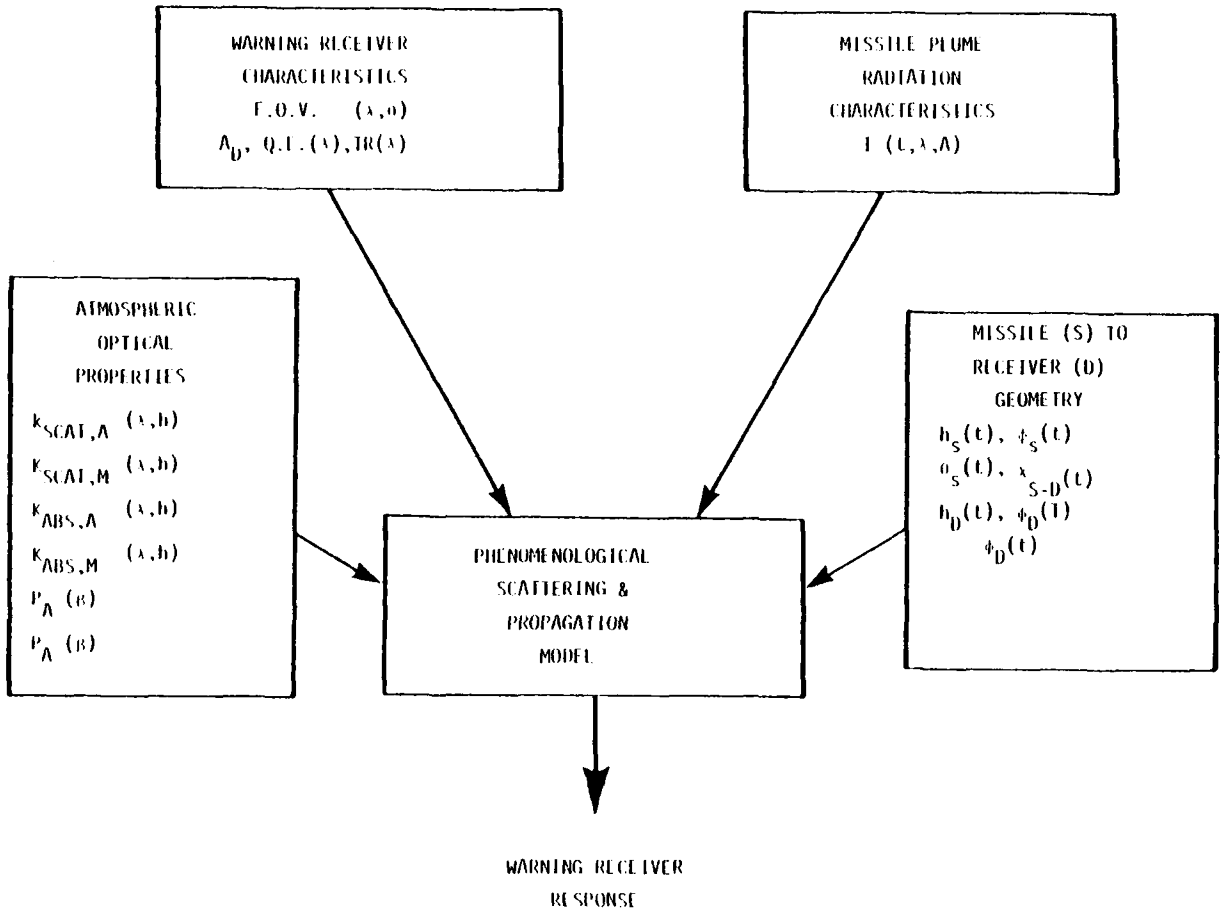


Figure 5. Factors Affecting the Response of a Warning Receiver.

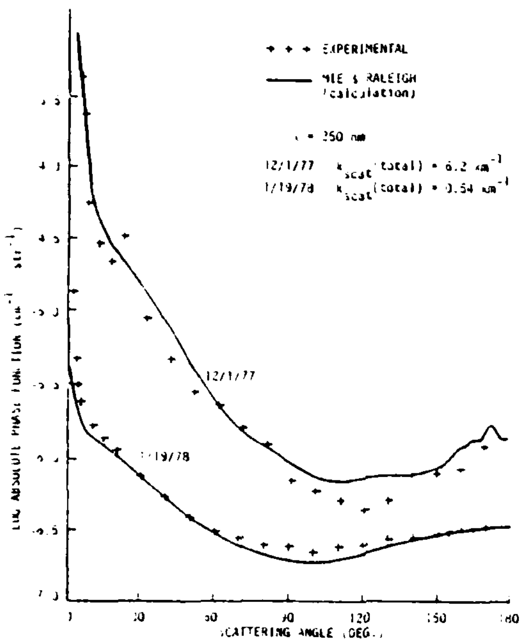


Figure 6. Measured and Calculated Angular Scattering.

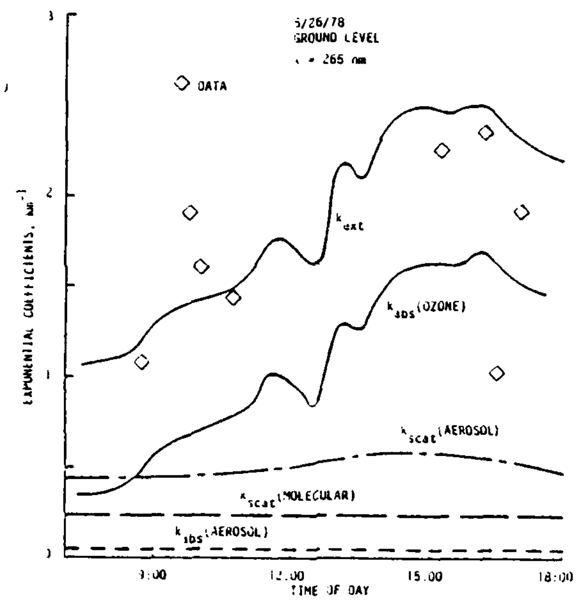


Figure 7. Variation of Exponential Coefficients with Time.

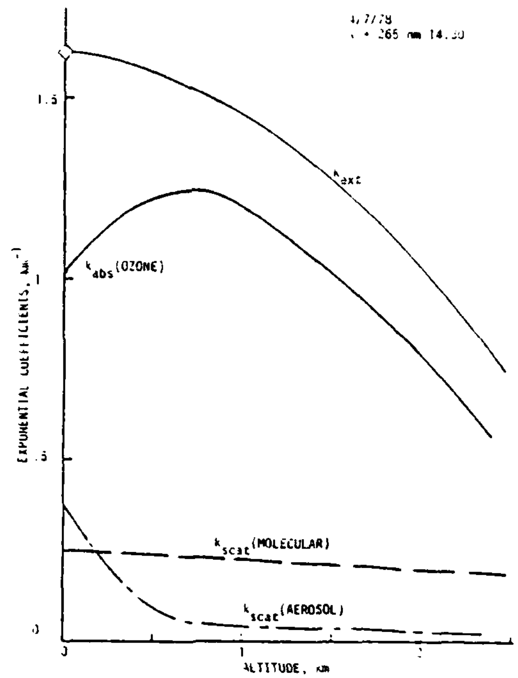


Figure 8. Variation of Exponential Coefficients with Altitude.

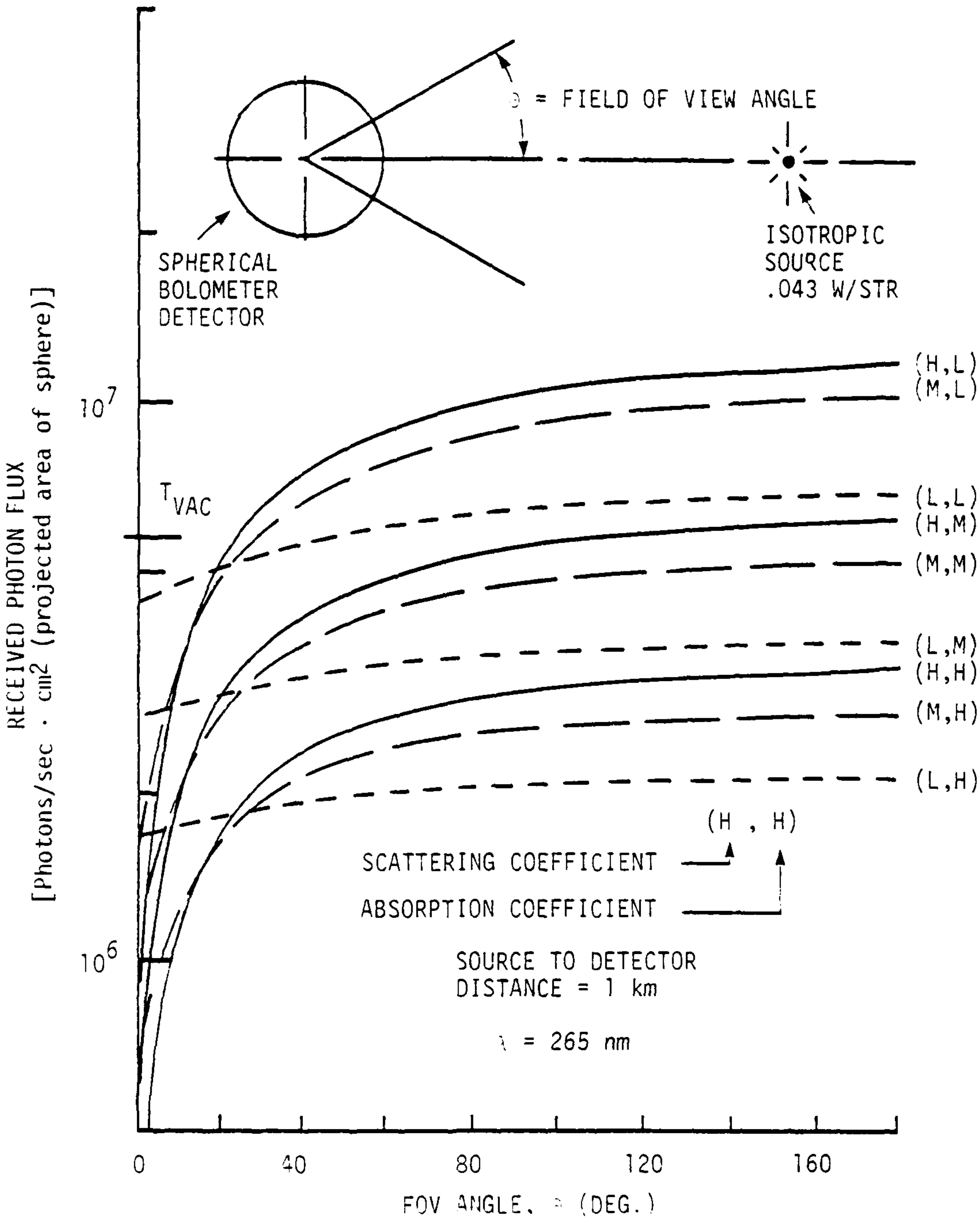
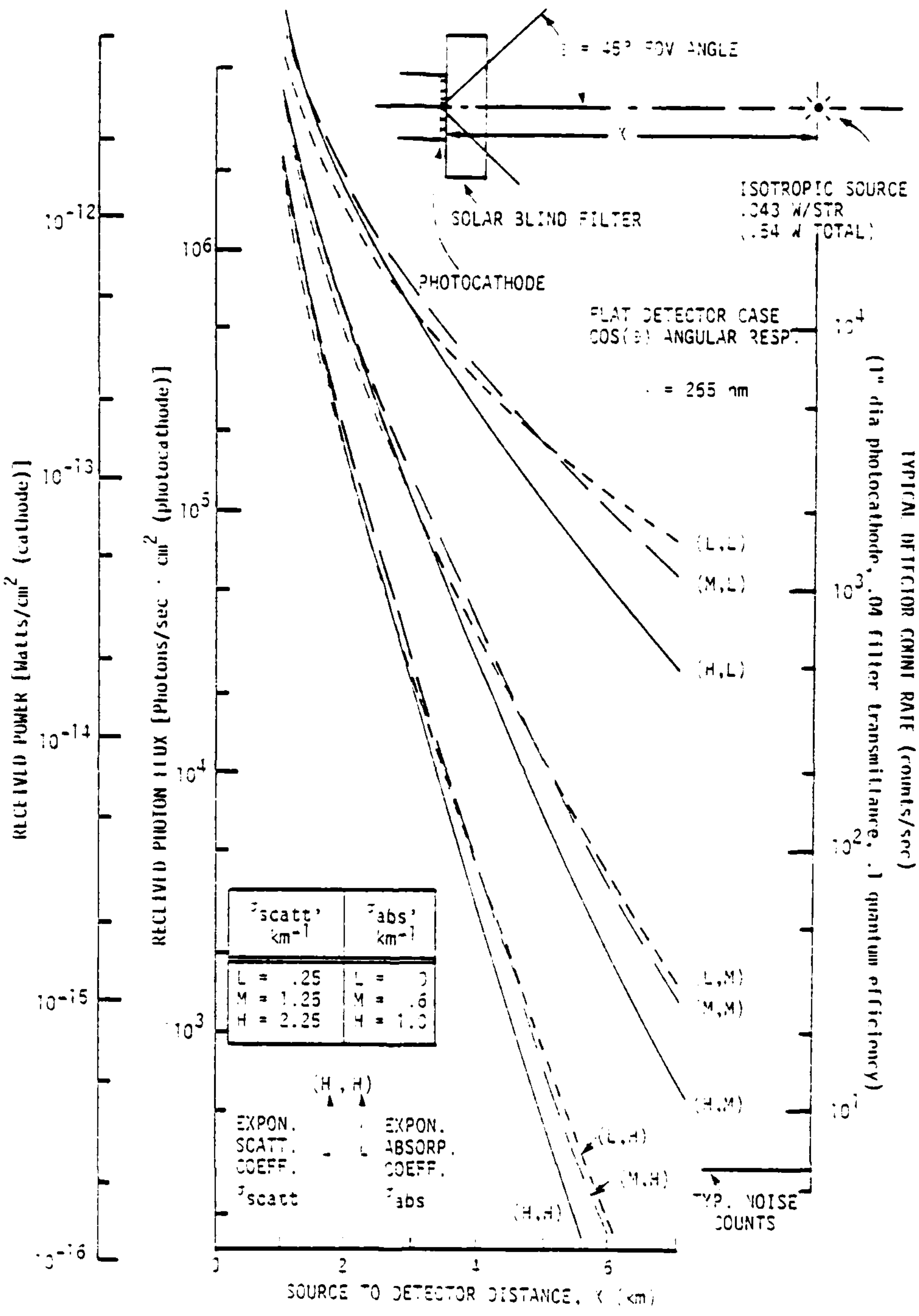


Figure 9. Combined Effects of Absorption and Scattering on Wide Field-of-View Detectors.



σscatt, km⁻¹	σabs, km⁻¹
L = .25	L = 0
M = 1.25	M = .6
H = 2.25	H = 1.0

Figure 10. Variation with Range of Energy Received by Wide Field-of-View System.

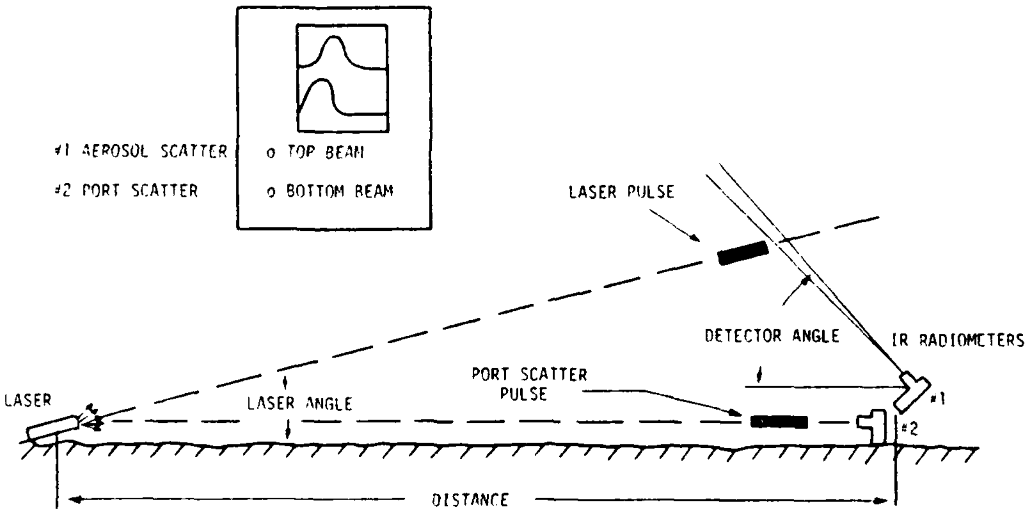


Figure 11. Laser and Detector Angles.

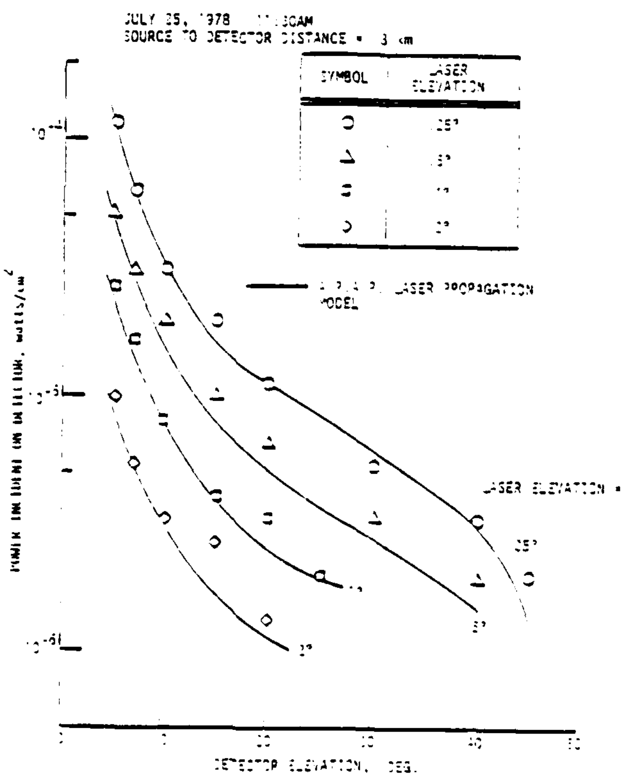


Figure 12. Measured and Calculated Scattering with Respect to Laser and Detector Elevation Angles.

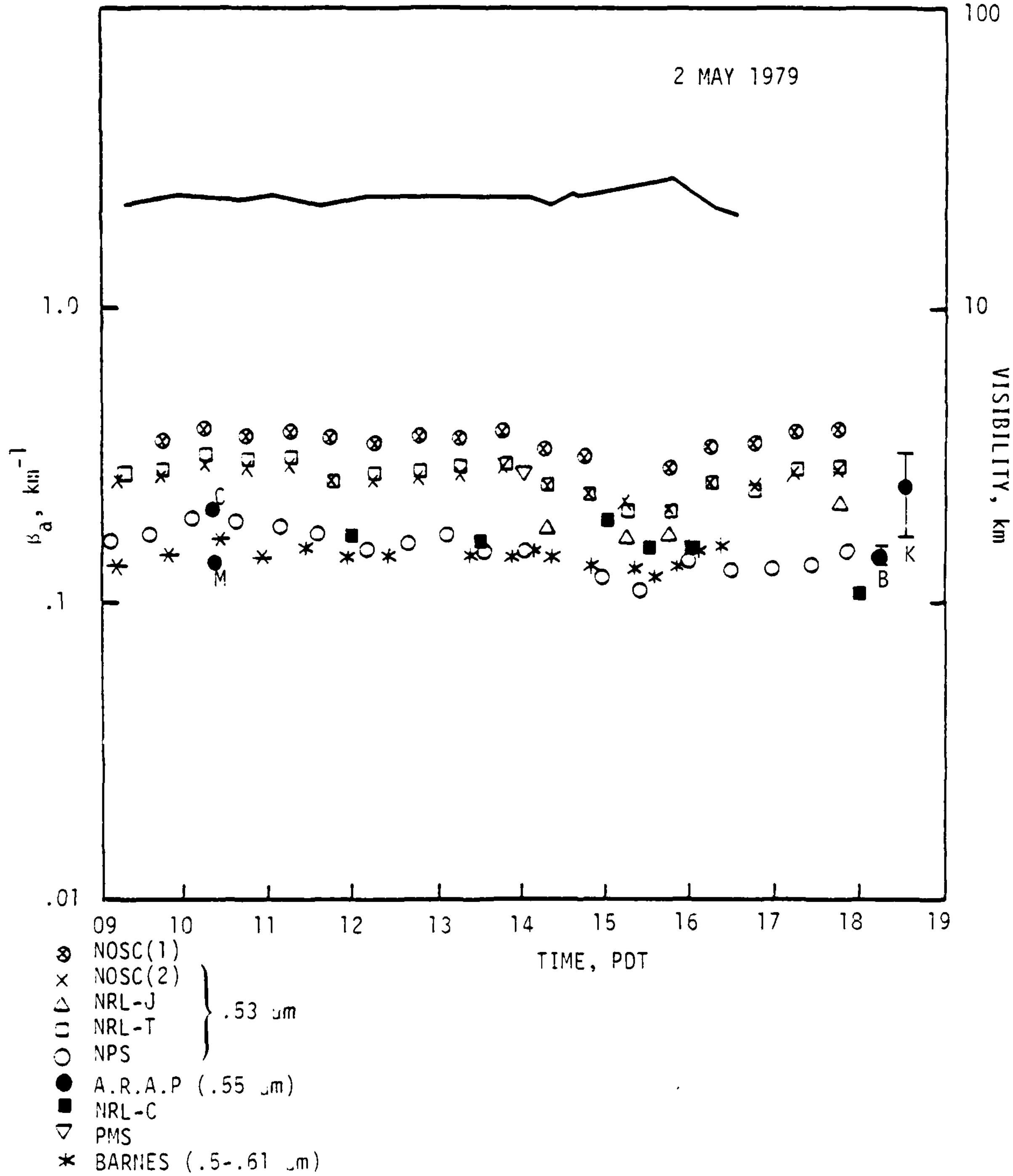


Figure 13. Variations of Mie Calculated Scattering Coefficients Based on Measurements with Different Particle Sizes.

PARTICLE MEASURING SYSTEMS: PARTICLE COUNTERS

John Knollenberg
Particle Measuring Systems, Incorporated
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A discussion of various Particle Measuring Systems (PMS) particle sizing equipment was presented.

Two families of instruments were described.

(1) Those measuring from scattered light (Active, Classic and Forward Scattering Spectrometer Probes).

(2) Those measuring from extincted light (2D Optical Array Probes).

Typical features of PMS scattering probes are:

(1) In situ sizing

(2) Variety of sizing ranges

(3) Solid state photo detectors

(4) Programmable size ranging

(5) Minicomputer compatability

Typical applications of PMS systems are:

(1) Air pollution monitoring

(2) Stack plumes monitoring

(3) Pharmaceutical manufacturing

(4) Cloud physics/precloud and haze measurements

(5) Mining

Calibration is generally performed with spherical particles (glass, latex beads).

Two problems for particle sizers in general were noted.

(1) The trajectory of a drop (as it passes through the sample volume) can affect measurement. Smaller particles are more prone to these effects, as they may be ignored at the extremities of the sample volume.

(2) Coincident droplets may bias measurements.

Figure 1 indicates the application of PMS spectrometers to particle size ranges.

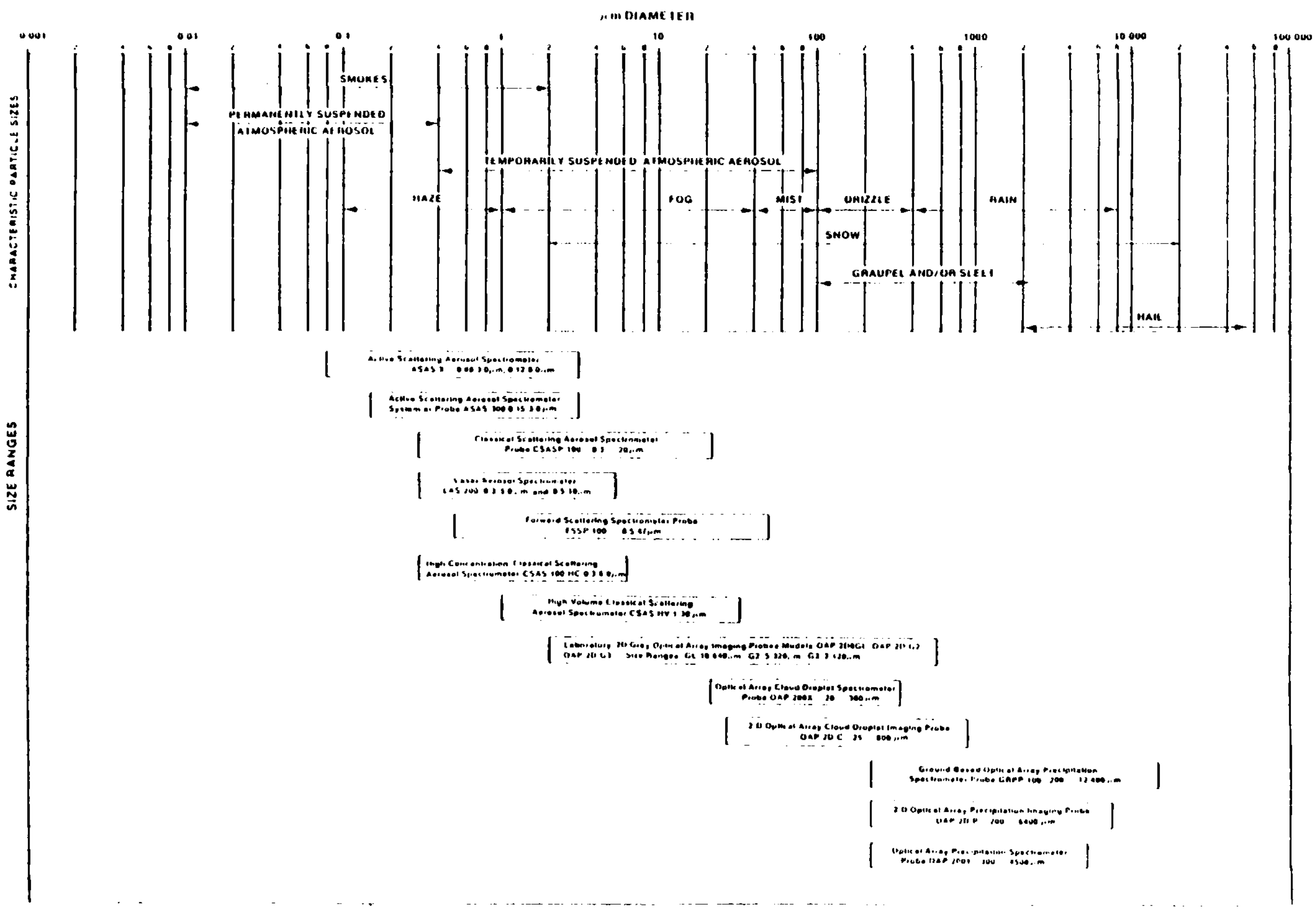

Figure 1. Size Ranges of Standard PMS Particle Size Spectrometers.

ROYCO PARTICLE COUNTERS

Alvin Lieberman
ROYCO Instruments Inc.
Menlo Park, California

Several Royco particle counters were introduced at this presentation. A composite of optical and physical characteristics for selected models is given in Table 1.

The optical layout for a ROYCO forward scattering system is shown in Figure 1.

A response curve for wide-angle scattering optics appears in Figure 2.

Latex spheres provide typical calibration criteria.

Attention was focused on the problems of sizing error and coincidence (particle clusters) as related to concentration measurements. Figures 3 and 4 illustrate these effects.

Finally, the uncertainty due to aerosol data quantity on measured concentration is given in Figure 5.

TABLE 1

OPTICAL PARAMETERS AND PHYSICAL DIMENSIONS: ROYCO PARTICLE COUNTER MODELS 203, 218, 220, 225, 245

OPTICAL DESIGN	203	218	220	225	245
Light half angle	24^0	5^0	24^0	5^0	5^0
Trap half angle		9^0		16^0	16^0
Collector half angle	24^0	25^0	24^0	25^0	25^0
Scattering angle range	42-138	4-30	42-138	11-30	11-30
Sensitivity, μm	0.2	0.5	0.3	0.3	0.5
Dynamic range, Standard	40:1	40:1	40:1	40:1	40:1
Sensing volume, cu mm	1.3	0.15	2.6	0.4	4
Coincidence Error, %	4	6	9	15	4.5
Concentration Limit, pcf	10^6	10^7	10^6	10^8	3×10^5
Resolution, % of mean at 1 sigma	3	15	5	5	15
Flow Rate, cfm	0.01	0.01	0.1	0.1/0.01	1
Data	Remote, Selectable	Digital, Fixed	Remote, Selectable	Integral, Selectable	Integral, Selectable
Dimensions, inches					
Main Frame	16x10x18	15x10x4	16x10x18	16x8x21	16x8x21
Sensor				5x4x21	5x4x21
Weight, pounds	32	18(23)*	32	42	42
Main Frame	32	18(23)*	32	42	42
Sensor	-	-	-	12	12
Power	150	55(25)*	150	250	250
Environment	7 C - 52 C operating, -40 C-70 C, non operating 95% Relative Humidity operating, 98% non operating 1G operating, 5G non operating				

*Battery Operation

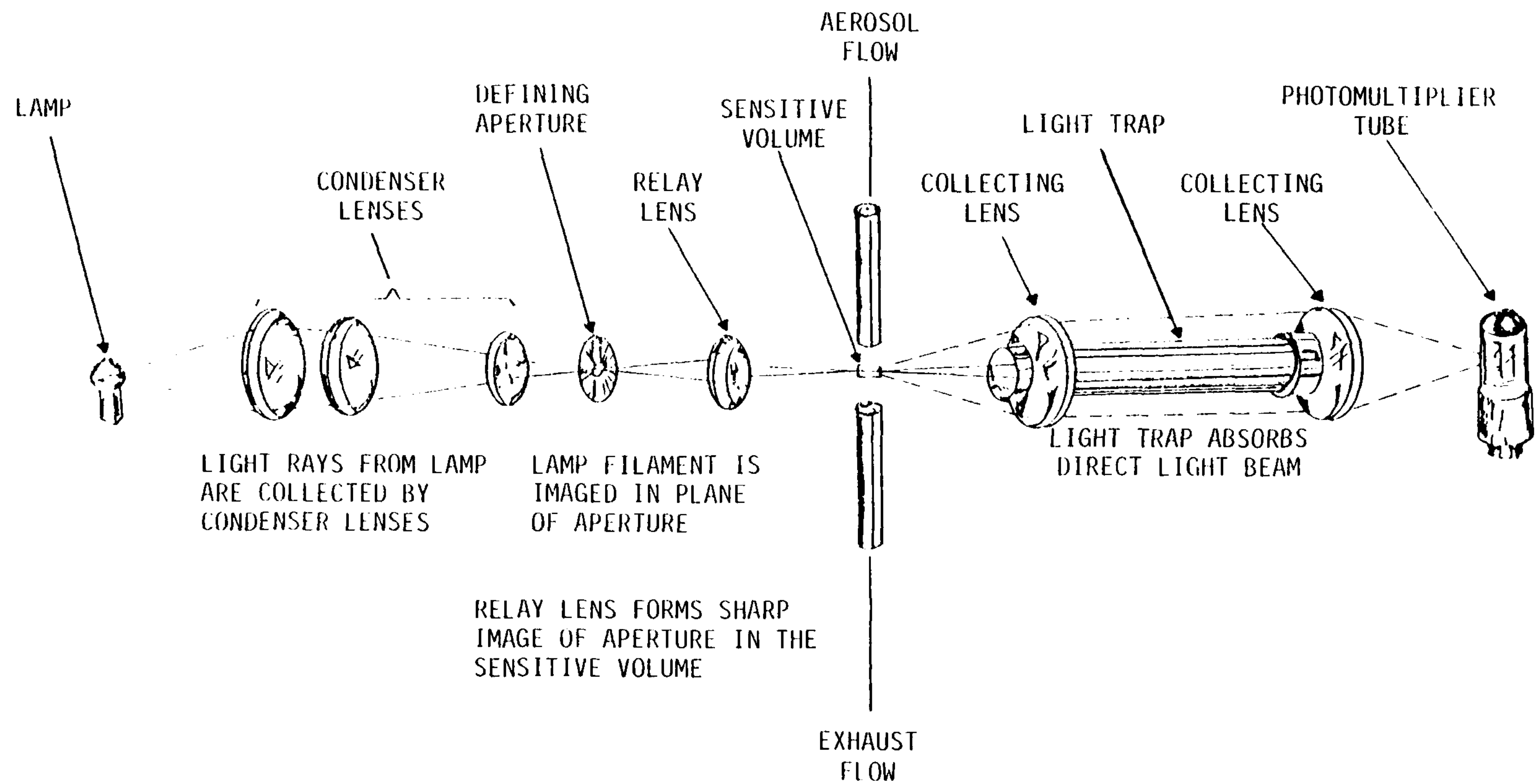

Figure 1. Optics Components: Forward Scattering Optical System.

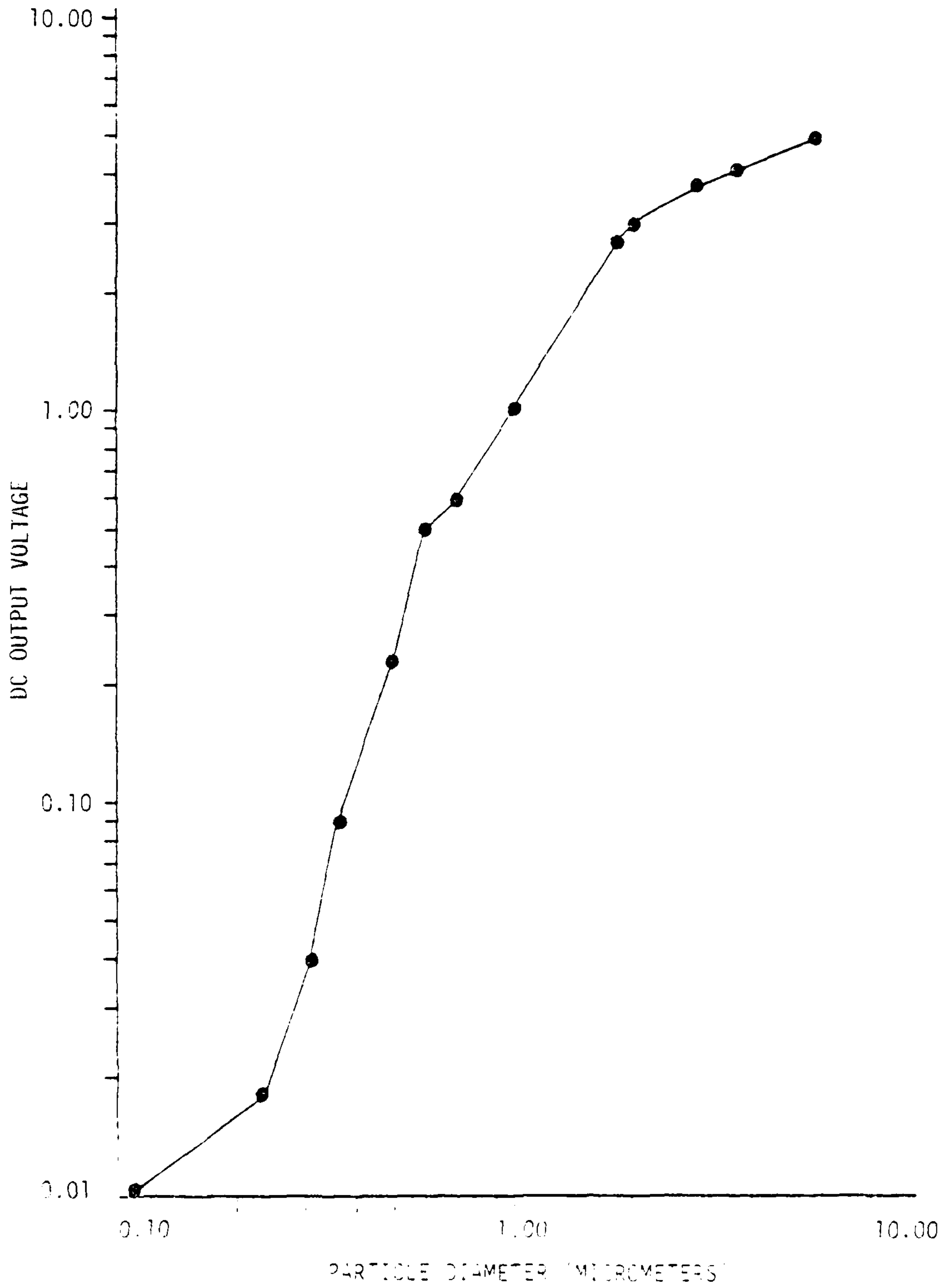

Figure 2. Response Versus Size for Wide Angle Scattering Optics. (Model 226)

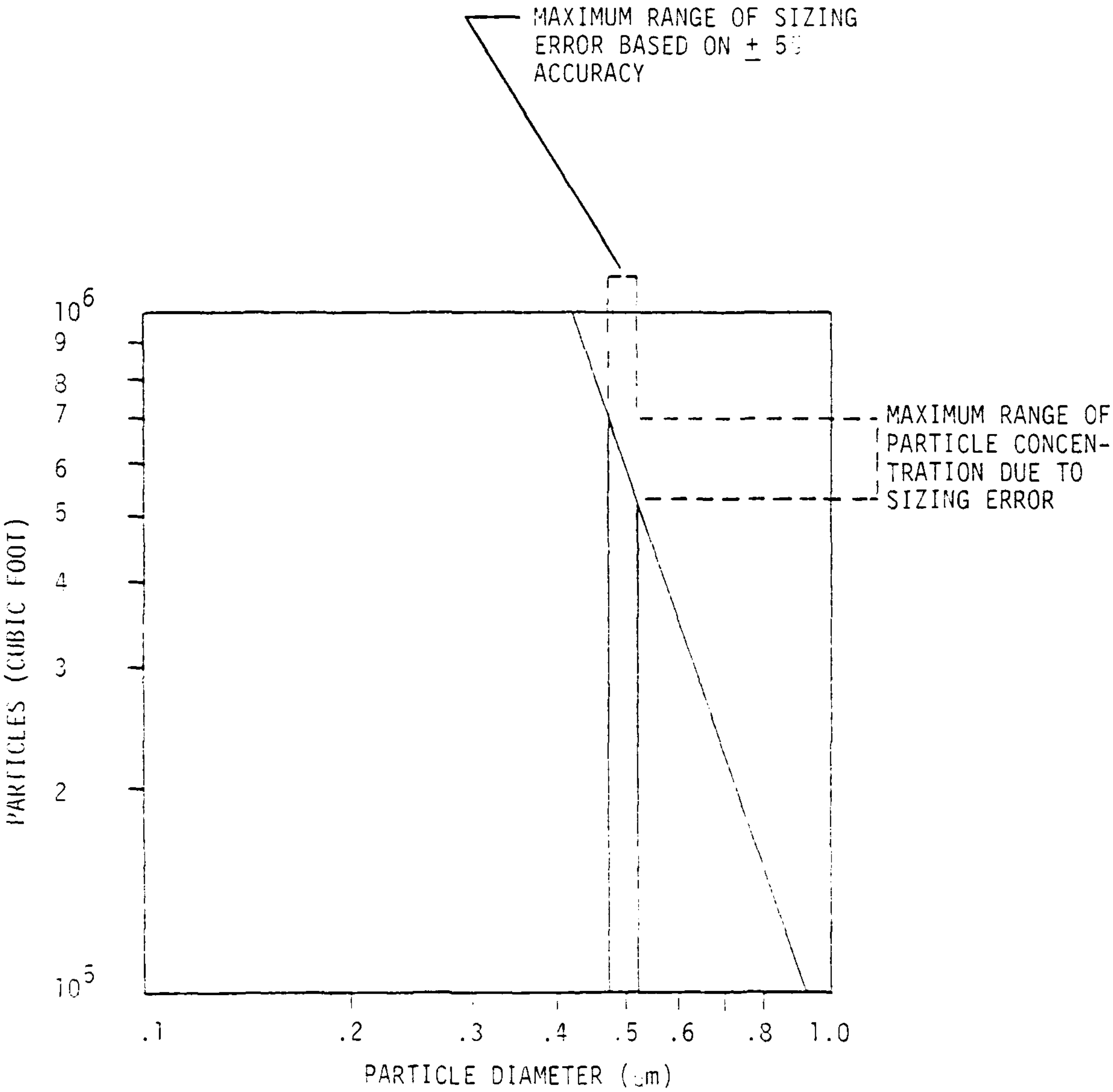

Figure 2. Size Accuracy Effect on Concentration Error.

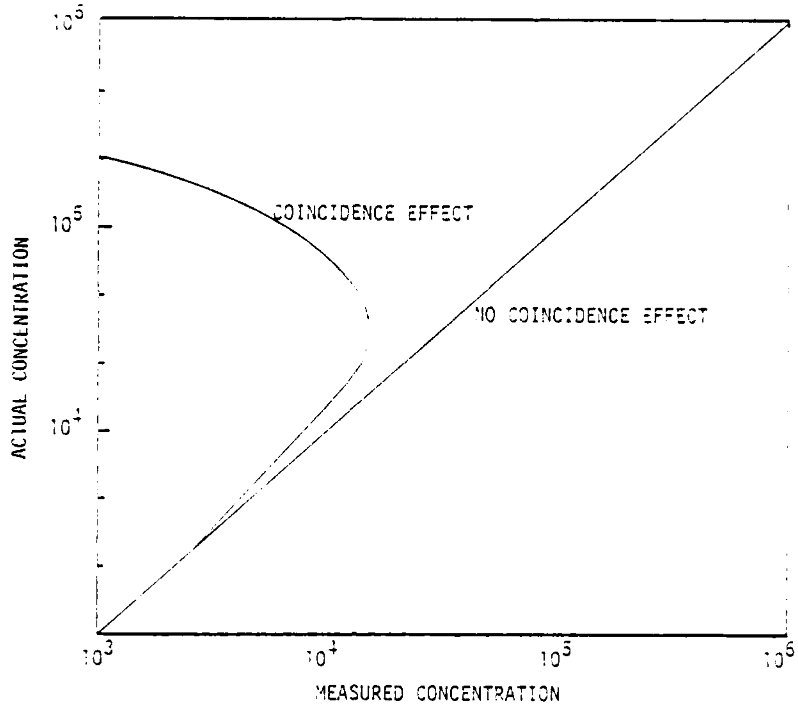

Figure 4. Coincidence Effect on Concentration Error.

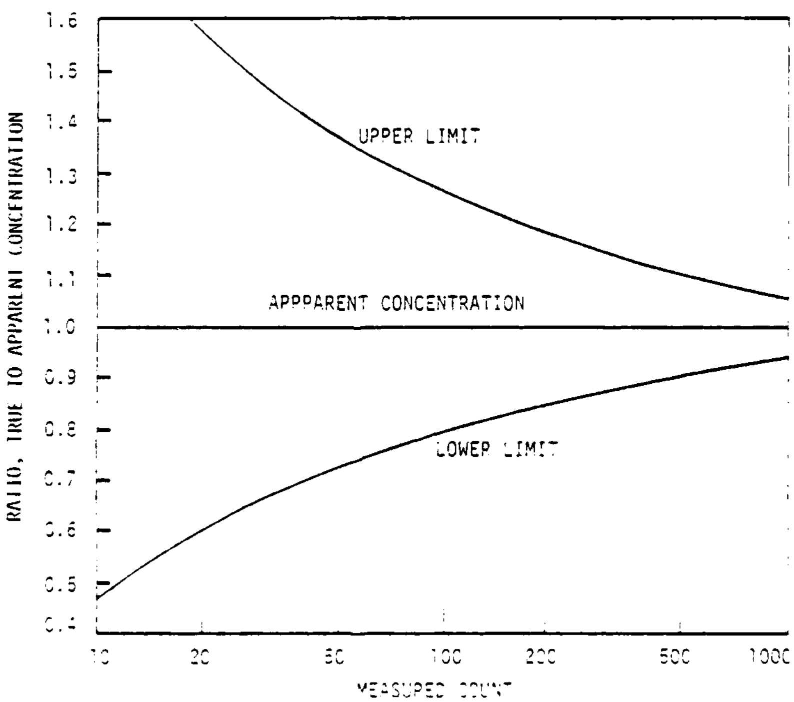

Figure 5. Statistical Error Due to Data Quantity: Uncertainty in Apparent Concentration.

TSI PARTICLE SIZING EQUIPMENT

Jugal Agarwal
TSI Incorporated
St. Paul, Minnesota

Several types of Thermo-Systems, Incorporated (TSI) aerosol analyzers were presented.

Electrical Aerosol Size Analyzer (EAA). Counting and sizing with the EAA is based on a process of charging the particles with a unipolar charge and then measuring the mobility distribution of the charged particles.

Condensation Nucleus Counter (CNC). Continuously flowing aerosol is saturated with alcohol and cooled while being sampled. The aerosol vapor condenses on the particles (nuclei) to form droplets approximately 5-10 μm in diameter. The stream exits through a nozzle and passes through a narrow light beam. Light scattered from the droplets in the forward direction, is collected and focused into a photodetector. For high concentrations (> 1000 particles/cm^3), the intensity of light scattered by all the droplets in the view volume is measured. For other concentrations, electrical pulses generated by the light scattered from individual particles are counted.

Typical application of TSI particle analyzers include the following.

(1) Air quality research.

(2) Aerosol manufacturing.

(3) Airborne aerosol sampling.

(4) Atmospheric cloud physics research.

(5) Medical research.

REFERENCE

Agarwal, J., G. Sem, M. Pourprix, "A Continuous CNC Capable of Counting Single Particles," Proceedings of 9th International Conference on Atmospheric Aerosols, Condensation and the Nuclei, Galway Ireland (1977).

PARTICLE SIZE MEASUREMENT USING ELECTRICAL RESISTANCE

Shepard Kinsman
Coulter Electronics, Inc.
Hialeah, Florida

It is common to measure particle size distributions and concentrations in size ranges from 0.5 to over 200 μm using the Coulter Counter*. A requirement is that the sample be pre-collected. Methods of collection are membranes, impaction plates, liquid impingers, cyclones, and thimbles. From the collectors the particles are introduced into a conductive liquid such as 1% NaCl in H_2O or 4% ammonium thiorcyanate with alcohol.

The suspended particles are measured and counted at rates up to 3000 per second as they are forced through a small hole or aperture. A sensing signal is generated each time a particle passes through the aperture. An electric current flows from one electrode to the other through the liquid and through the aperture. Each passing particle displaces conductive liquid in proportion to its volume causing a signal pulse. Pulses are separated into size intervals and counted. Size distribution data output can be X-Y plotted, printed, read digitally or observed on the cathode ray tube.

Aerosol dust size distributions along with concentration values are quickly obtainable in the laboratory for verification of field tests.

All sorts of test dusts such as A-C fine dust can be profiled with excellent definition and a high degree of statistical accuracy. Calibrations with standard particles is fast and reproducible.

The limitations are as follows.

(1) 0.5 to 200 μm size range.
(2) Sample must be collected and then liquid suspended.
(3) Analysis must be done in a lab.
(4) Particle volume rather than aerodynamic diameter is measured. According to Tombs and Corn, conversions can be made.
(5) Particles must be stable in the suspending liquids.

The advantages are as follows.

(1) Fast analysis (such as 30 seconds).
(2) Both size and concentration data are available.
(3) Sensitive down to 0.5 μm diameter.
(4) Less than a milligram of sample is required.
(5) Sensitive to bimodel particle systems.
(6) High statistical accuracy.
(7) Fast, reproducible microsphere calibration.

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*The use of trade names in this report does not constitute an official endorsement or approval of the use of such commercial hardware or software. This report may not be cited for purpose of advertisement.

MARINE MEASUREMENTS: SAN NICOLAS ISLAND

Gary Trusty
Optical Sciences Division
Naval Research Laboratory
Washington, D.C.

The Navy has been involved in large scale laser transmission/extinction measurement programs at San Nicolas Island in the Pacific. The site affords a local geography which is particularly conducive to measuring gradients of transmission and particle size distributions above the surf. Certain of the particle sizing aspects and results of the programs were presented.

Of particular interest is the dependence of size distribution (and extinction properties) on relative humidity in this marine environment. Since measurements are often made in 80%+ R.H., many of the particles are water saturated. Figure 1 displays a typical effect of R.H. on the size distributions.

A wind factor has also been observed. In low wind conditions, the highest particle counts (hence extinction coefficients) are observed near the surf: a definite gradient is apparent. Under higher wind conditions (3-15 m/sec) the gradient is less noticeable if, in fact, existent. The counts are all time-averaged so that an "instantaneous" profile remains unknown.

Knollenberg particle counters have been utilized for these measurements because of their in-situ capability. Calibration (standardization) of the instruments are performed frequently and pose no difficulty.

To sum the state of the art with regard to marine measurements of particle size distributions, it is generally accepted that accuracy can be achieved to within a factor of two with available instrumentation (Figure 2). This is by no means acceptable but does indicate that progress has been made.

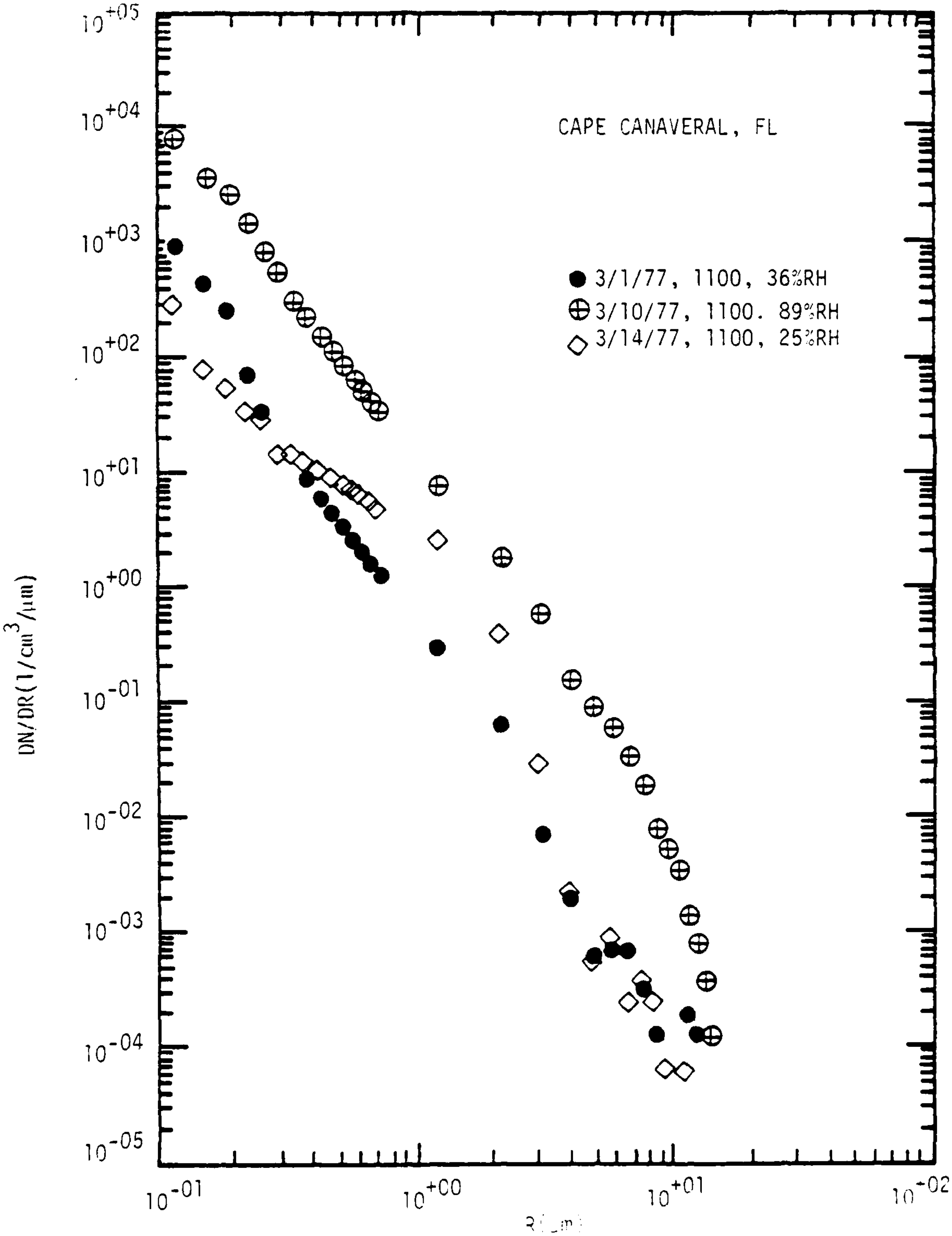

Figure 1. Size Distributions and Relative Humidity.

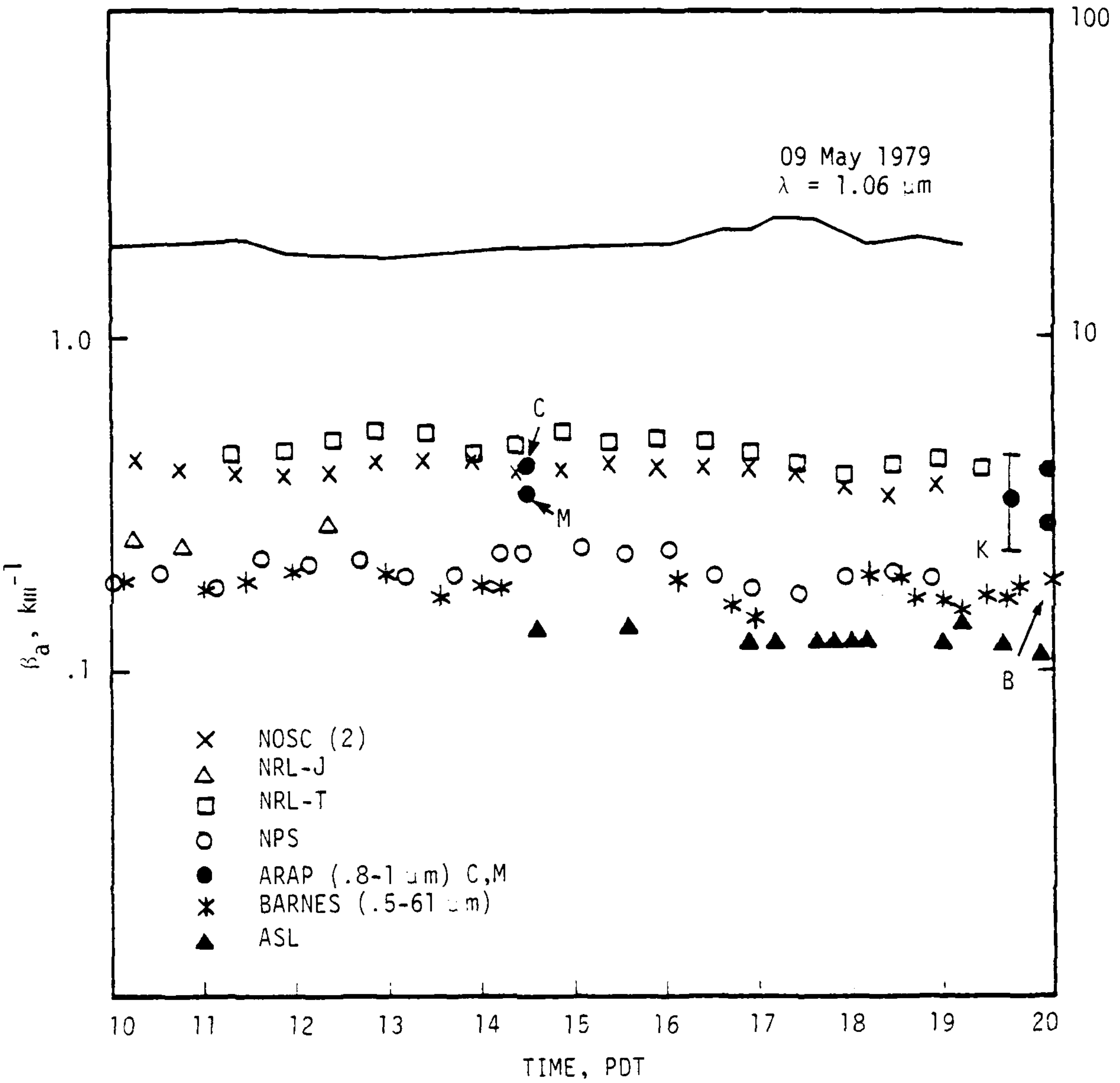

Figure 2. Comparison of Measured Extinction Coefficients ("Factor of 2" Effect Noticeable).

HIGH HUMIDITY SMOKE TESTS

W. Michael Farmer
University of Tennessee Space Institute
Tullahoma, Tennessee

Discrepancies between field and laboratory measurements of particle size and distirbution for various smokes and fog oils pose problems to researchers. The impact of humidity on particulate size and distribution have been extensively investigated and the results were reviewed in this presentation.

Theoretically, as relative humidity (R.H.) increases so should hydroscopic particle size. Modelers incorporate this idea in their transmission codes. Actual measurements, however, show something of a counter-trend, as increases in R.H. tend to be accompanied by decreases in smoke particulate diameter. Table 1 quantifies this comment and implies that in certain cases this characterization is too simplistic: diameters for some obscurants actually behave somewhat "theoretically" once humidity levels reach 90%+. It has also been noticed that as R.H. decreases, the size distributions tend to spread out.

Testing at UTSI with particle size interferometers (PSI) and Knollenberg counter (PMS) particle sizing equipment indicates that discrepancies between the measurements of the two systems (Table 2) is a result of the technique of the PMS device: not all of the particles in the field were seen.

The typical size distribution problem of defining the size bins was reviewed. It was emphasized that much care must be given in this regard, otherwise the measurements can be quite misleading.

TABLE 1

COMPARISON OF HIGH HUMIDITY HYDROSCOPIC SMOKE (H^3S) TRIAL RESULTS (PSI DATA ONLY)

TRIAL	TYPE OBSCURANT	RELATIVE HUMIDITY	GEOMETRIC MEAN DIAMETER (μm)	LOGARITHMIC GEOMETRIC STANDARD DEVIATION	NUMBER DENSITY RANGE ($CC^{-1} \cdot 10^{-6}$)	%≤0.3 m	TYPICAL MASS CONC. (gm/m^3)
	RP GRENADES						
10	4.8 lbs.	97%	0.362 ± 0.02	0.468	0.33 - 1.53	90 ± 3.1	1.23
15	3.2 lbs.	89%	0.357 ± 0.02	0.455	0.238 - 0.6	90 ± 2.5	0.40
7	6.4 lbs.	73%	0.370 ± 0.01	0.474	0.59 - 0.97	88.6 ± 2.6	0.79
19	3.2 lbs.	67%	0.428 ± 0	0.539	0.275	81.5	0.71
	WP WEDGES						
17	13.7 lbs.	92%	0.365 ± 0.02	0.461	0.411 - 0.681	88.4 ± 2.4	1.1
12	13.7 lbs.	89%	0.358 ± 0.02	0.471	0.465 - 0.4	90.7 ± 1.7	1.59
8	13.7 lbs.	79%	0.362 ± 0	0.463	0.245 - 0.325	89.7 ± 1.9	0.53
4	13.7 lbs.	73%	0.381 ± 0.03	0.492	0.325 - 0.038	87.4 ± 5.2	1.26
	WP WICKS						
16	2.1 lbs.	94%	0.347 ± 0.01	0.45	0.317 - 0.725	92.3 ± 2.0	0.49
2	6.3 lbs.	82%	0.352 ± 0.02	0.466	1.03 - 2.49	91.9 ± 1.1	0.98
13	4.2 lbs.	80%	0.363 ± 0.01	0.463	0.343 - 1.17	90 ± 2.0	1.82
28	4.2 lbs.	75%	0.447 ± 0.01	0.530	0.454 - 0.89	78.9 ± 0.9	1.69
25	4.2 lbs.	71%	0.400 ± 0.03	0.501	0.237 - 0.652	82.0 ± 4.5	0.56
	HC						
11	10.8 lbs.	97%	0.341 ± 0.01	0.448	0.32 - 4.95	93.1 ± 0.3	
23	10.8 lbs.	87%	0.367 ± 0	0.466			
14	5.4 lbs	84%	0.402	0.470	0.411		
6R	10.8 lbs.	72%	0.407 ± 0	0.540			

TABLE 2

COMPARISON OF TYPICAL LABORATORY CALIBRATION DATA FOR 81-83% R.H.

OBSCURANT	GEOMETRIC MEAN DIAMETER (μm)		LOGARITHMIC GEOMETRIC STANDARD DEVIATION		THIRD MOMENT (μm^3)		NUMBER DENSITY	%<0.3 μm	MASS CONCENTRATION (gm/m^3)	
	PSI	PMS CSASP	PSI	PMS CSASP	PSI	PMS CSASP	($cc^{-1} \cdot 10^{-6}$)		PSI	FILTER SAMPLE IMPACTOR
Hc	0.334	0.34	0.421	0.175	0.72	0.01	0.576	93	0.44	0.17
Red Phosphorus	0.328	0.415	0.431	0.262	0.97	0.0865	1.62	94.8 ± 0.8	1.60	1.4
Fog Oil	0.326	0.42	0.432	0.26	0.969	$9.5 \cdot 10^{-4}$	1.07	95.2 ± 0.9	0.49	0.34

MEASUREMENTS OF ATMOSPHERIC SCATTERING ASSOCIATED WITH SHORT DURATION LASER PULSES AT 1.06 μm

Michael E. Neer and Joseph M. [illegible]
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During the preliminary design of the AVR-2 Laser Warning Receiver, a theoretical and experimental parametric investigation was carried out to determine the effects of atmospheric aerosols on laser warning receiver performance. This presentation describes the experimental portion of that investigation. The purpose of the experimental measurements was to verify the atmospheric propagation and scattering model used in the warning receiver analysis. The measurements were carried out in July of 1978 at the Wayside Laser Test Range, Fort Monmouth, New Jersey with the cooperation of the U.S. Army ERADCOM, Electronic Warfare Laboratory.

The laser used for this investigation was a neodenium yag laser with approximately 4 megawatts peak power and a pulse width of 20 nanoseconds. The radiometer was composed of a fast silicon detector with a narrow band pass filter at 1.06 microns. The field-of-view of the radiometer is shown in Figure 1, while the time response of the radiometer to the incoming radiation pulses is shown in Figure 2. The signals from the radiometer were displayed on a single sweep dual beam 400 megahertz oscilloscope and recorded on Polaroid film. Knollenberg Particle Measuring System size analyzers were used to measure the aerosol particle size distribution. A sample particle distribution is shown in Figure 3. A typical variation of the aerosol scattering coefficient with time of day is shown in Figure 4. The scattering coefficients were determined by utilizing the measured particle size distributions together with Mie scattering theory. A comparison of a measured single scattering phase function with that predicted from Mie theory using measured particle size distributions is shown in Figure 5. Figures 6 and 7 show comparisons of measured and predicted laser scattered radiation for laser elevation angles and detector elevation angles at various times and source to detector distances.

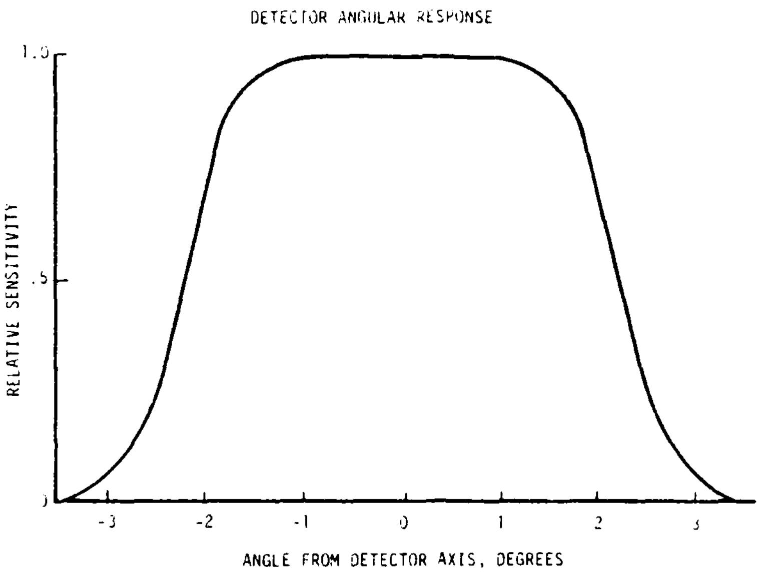

Figure 1. Field of View: Radiometer.

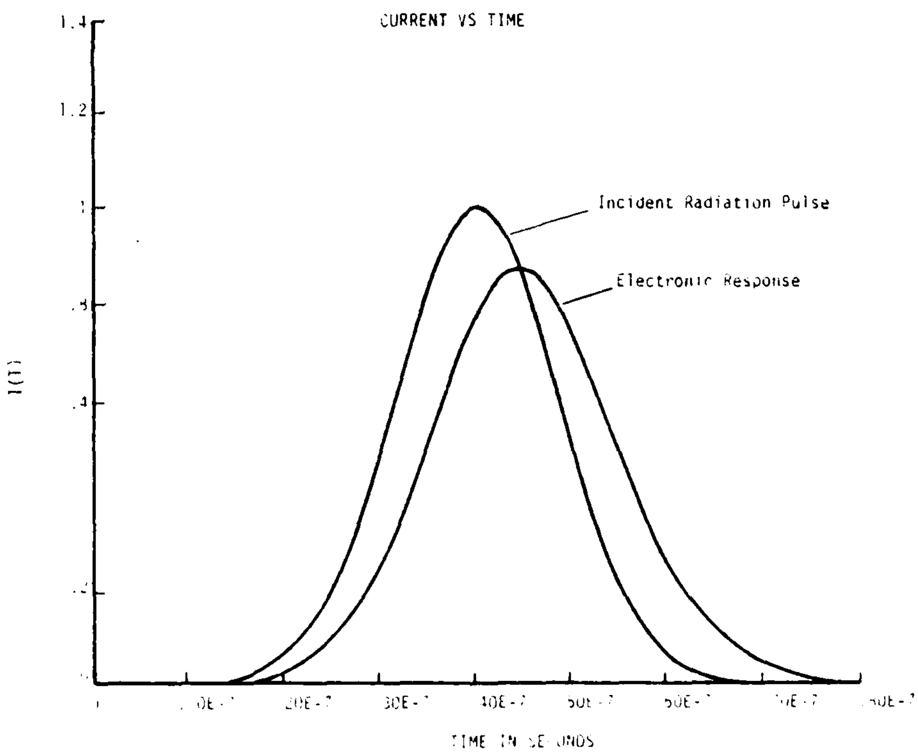

Figure 2. Time Response: Radiometer.

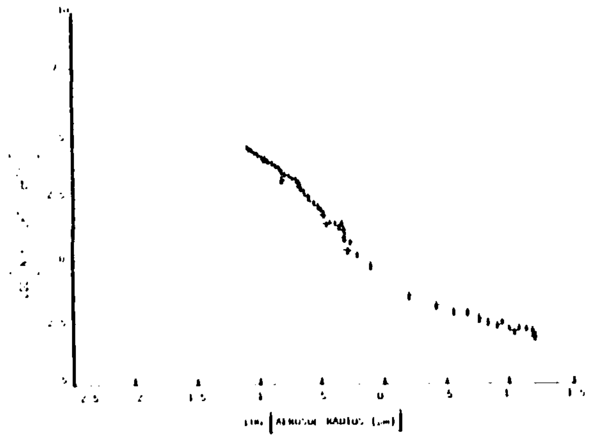

Figure 3. Particle Distribution.

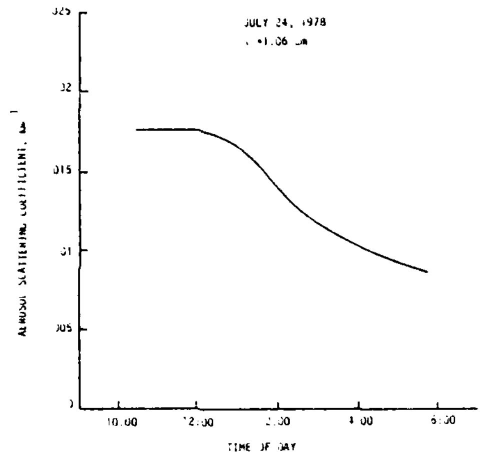

Figure 4. Variation of Scattering Coefficient with Time.

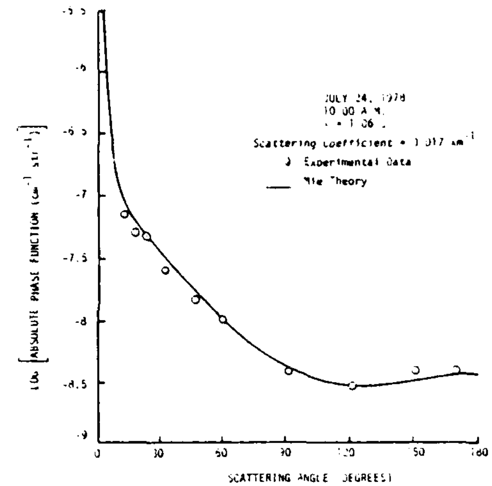

Figure 5. Measured and Predicted Scattering Phase Functions.

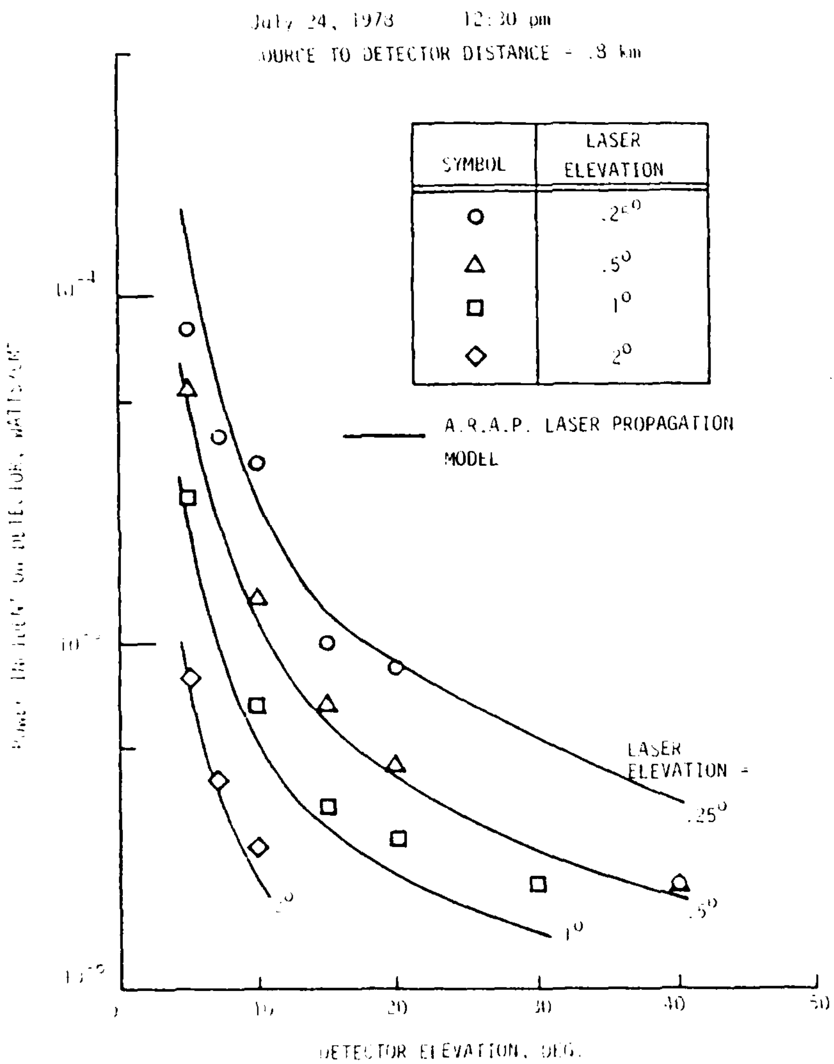

Figure 6. Measured and Predicted Scattered Radiation: Mid-Day

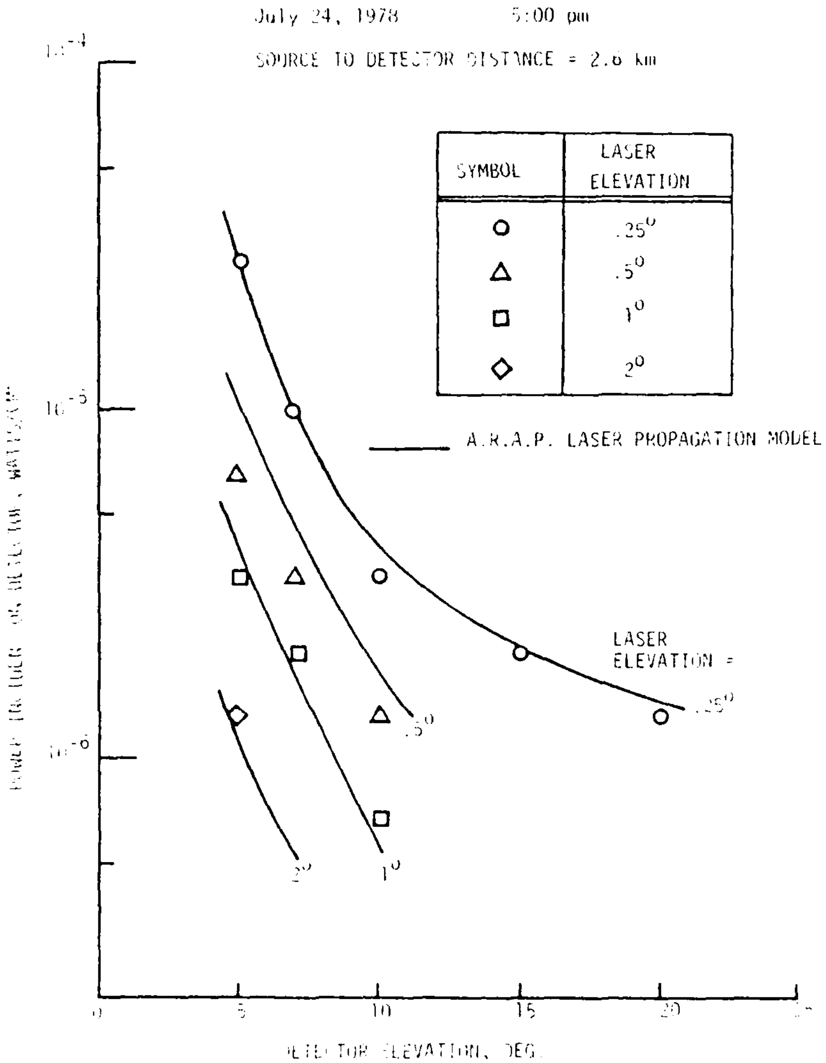

Figure 7. Measured and Predicted Scattered Radiation: Late Afternoon

MEASUREMENTS OF ICE PARTICLES

Jay D. Hunt
SVERDRUP/ARO, Inc.
AEDC Division
ETF/TAB
Arnold Air Force Station, Tennessee

The Air Force has an interest in the simulation of icing clouds. For the experimentalist, this means that accurate droplet sizes must be obtainable for comparison with the specifications modeled in the research programs.

Problems that confront particle sizing/counting devices used in icing studies include large number densities, a wide range of particle diameters (10-150 μm) and the relatively large particles that such sizes present.

In addition to coping with these conditions, the ideal instrument must be an in-situ, real-time device.

ATMOSPHERIC PARTICULATE SIZE DISTRIBUTION MEASUREMENTS (1973/75) MADE WITH THE AFGL/EPSILON BALLOONBORNE SIZING SPECTROMETER

Henry A. Miranda, Jr.
Epsilon Laboratories, Inc.
Bedford Massachusetts

The AFGL/EPSILON balloonborne particulate sizing spectrometer, an instrument specially designed for operating up to stratospheric altitudes, is described very briefly. A unique feature of this instrument is its very high sizing resolution. This specific system characteristic, which we believe to be an important ingredient of any particulate sizing spectrometer, has been determined empirically by simply sampling monodisperse particulates treated as unknown particles and recording the resulting system response spread function. The outcome of these tests indicates that size distributions with very steep slopes (of up to D^{-18}) can be reliably measured with this device.

Size distributions with such extreme slopes can be found in the stratosphere at altitudes beyond about 20km, whereas in the troposphere the size distributions are generally characterized by much more shallow slopes ranging between D^{-4} to D^{-12}. Selected data taken from four stratospheric flights in 1973 and 1975 are shown to illustrate the variability of size distribution slope. This variability appears to be a characteristic aspect of atmospheric size distributions, both in the stratosphere and in the troposphere as well.

As an example of the latter, three sample sets of data, taken at 3 km, 5.5 km, and 12.5 km, on the upleg portion of one of the 1973 balloon flights, are also presented (Fig. 1). These observations, made under very benign meteorological conditions (i.e., very clear sky, low humidity, low turbulence, low wind) indicated particulate size distribution slopes of D^{-8}, $D^{-7.5}$, and D^{-6}, respectively. The corresponding integral concentration of particles greater than 0.25 micron diameter were 171 particles/cm^3, 22.9 particles/cm^3, and 2.66 particles/cm^3 respectively. These three size distributions clearly show that, even near the surface of the earth, slopes very much steeper than the D^{-4} slope (which is commonly considered to be characteristic of size distributions) are very likely to be found under clear, quiet, dry atmospheric conditions at the Holloman, New Mexico, locale.

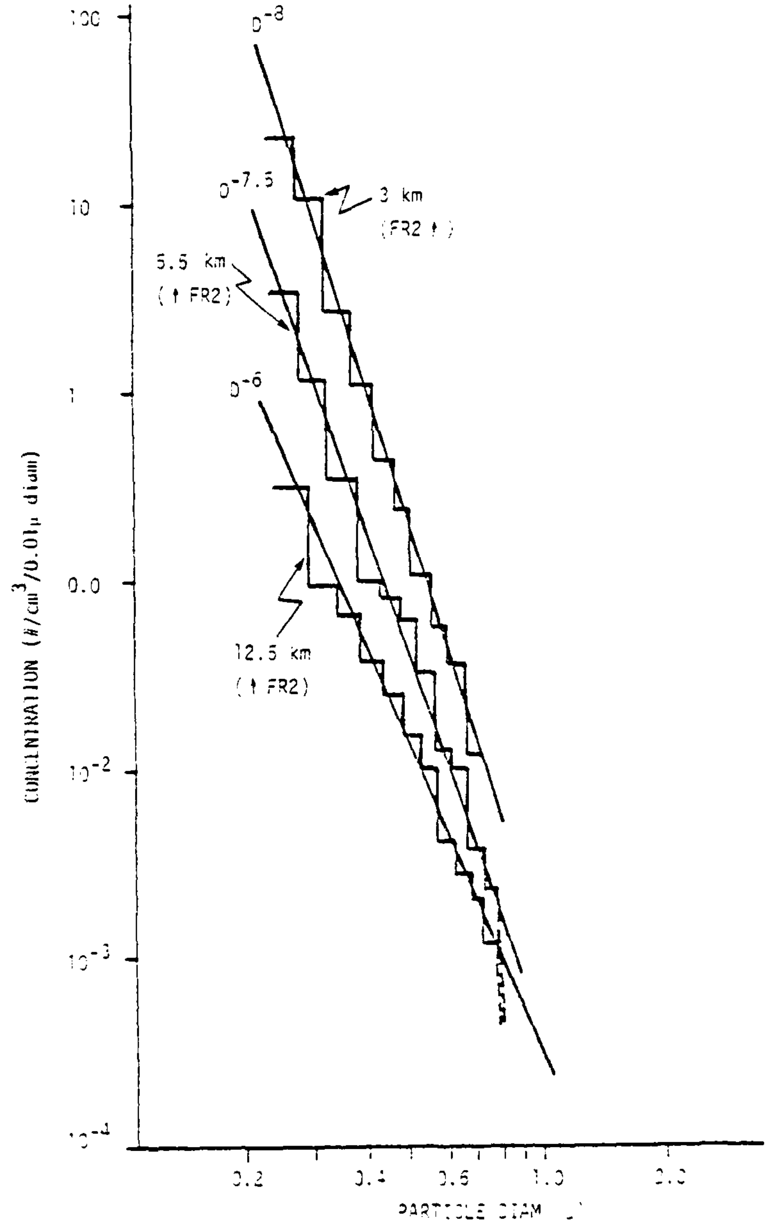

Figure 1. Tropospheric Size Distributions 1973: Holloman Air Force Base, New Mexico.

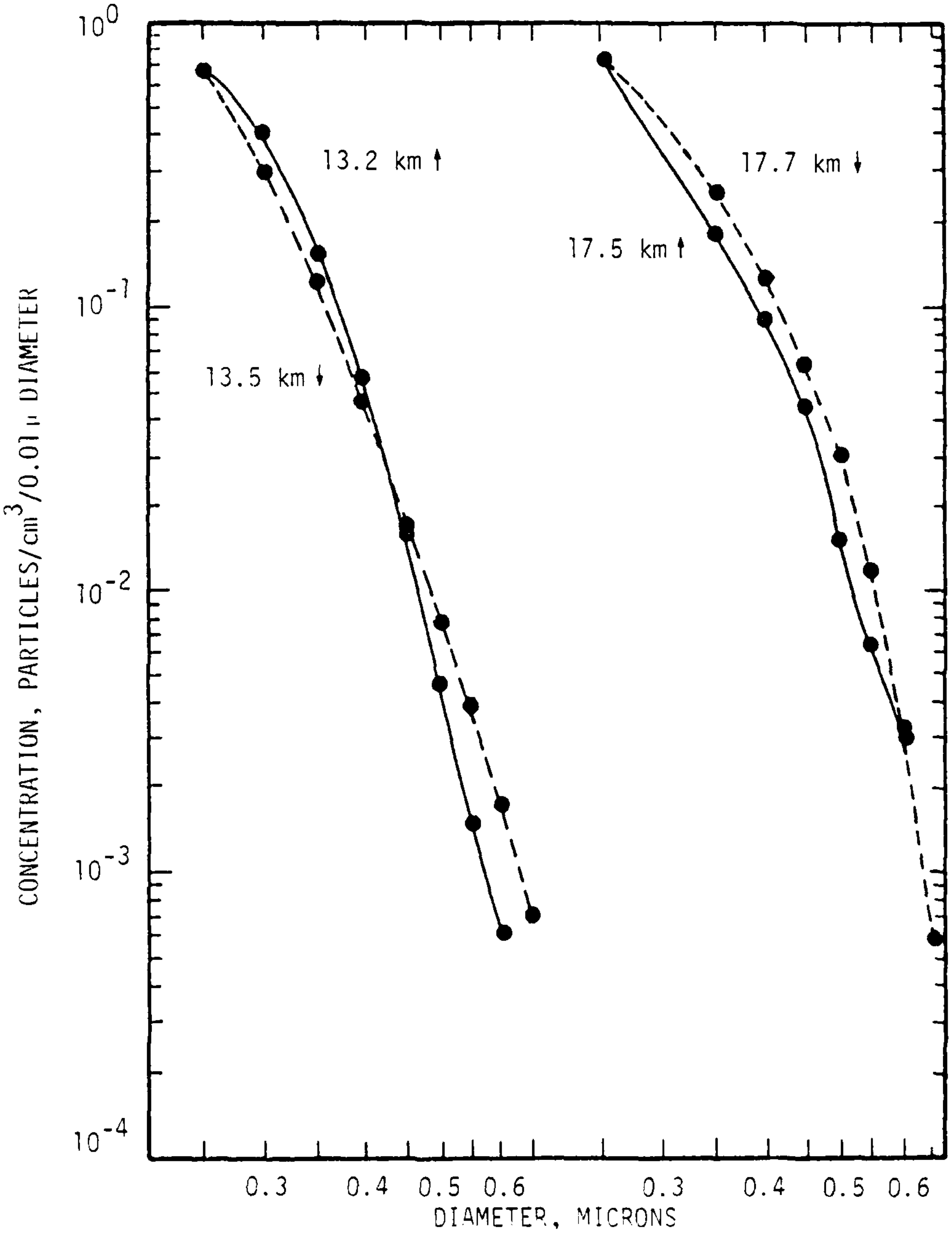

Figure 2. Examples of Size Distribution Similarities at Locations Separated by Several Hundred Miles.

THE LDWSS/BELDWSS PROGRAM

Matthew V. Maddix
Redstone Arsenal Army Missile Command
Huntsville, Alabama

The Army has recognized the impact that battlefield obscurants have on the performance of EO systems and is assessing the performance of such systems with elaborate computer simulations. Such a simulation must account for the system's performance parameters and must have accurate characterizations of the environments within which the system must function. The LDWSS (Laser Designator/Weapon System Simulation)/BELDWSS (Battlefield Environment Laser Designator/Weapons System Simulation) simulation development and validation program (a four-phase program) is outlined in this presentation.

LDWSS, a program for treating system level problems, consists of:

(1) development and validation of environment and subsystem models;

(2) integration of such models into an overall weapon system simulation (Figures 1 and 2); and

(3) weapon system performance analysis.

Data requirements for the BELDWSS Phase III Test Program scheduled for FY80 are shown in Table 1.

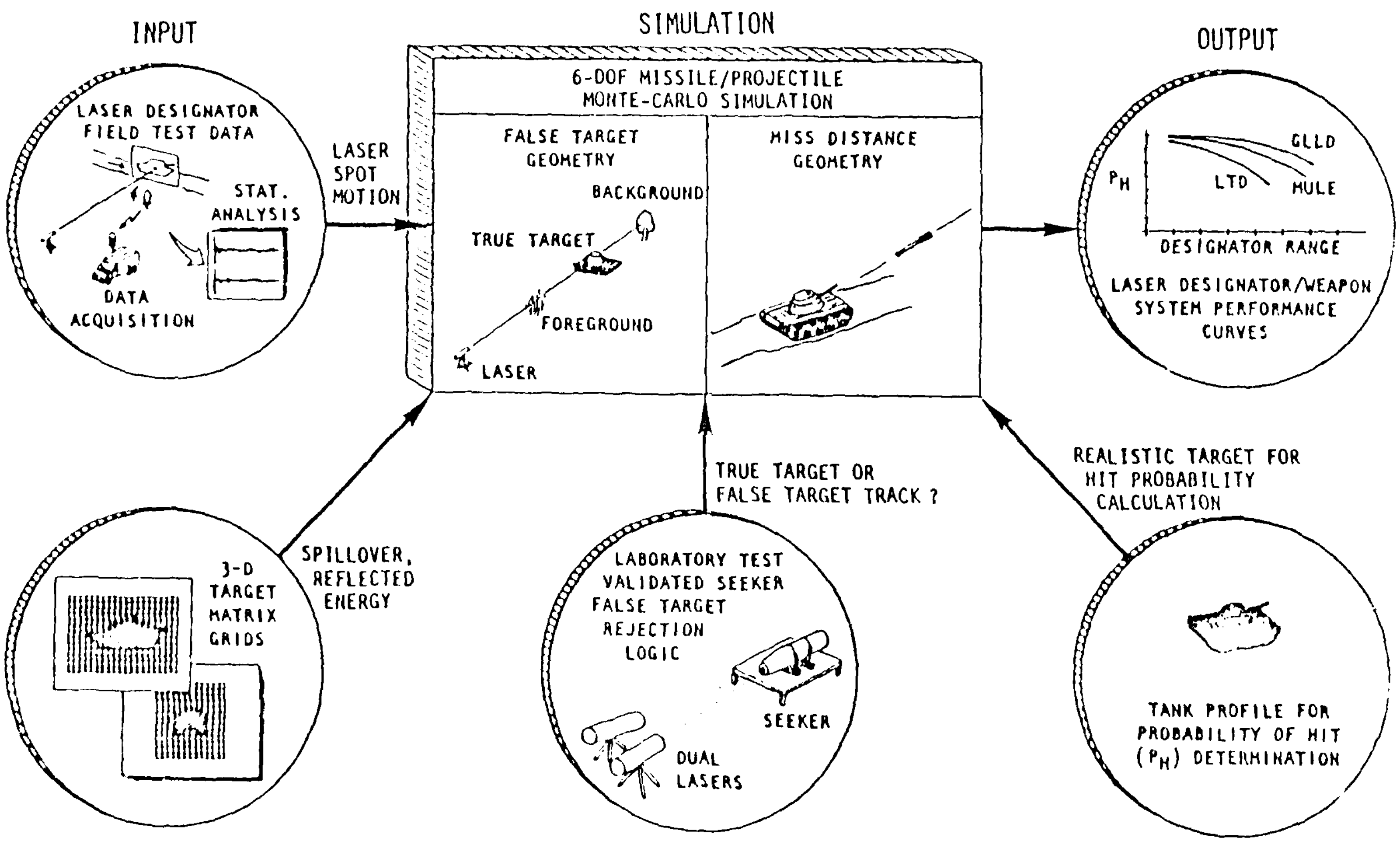

Figure 1. Laser Designator/Weapon System Simulation.

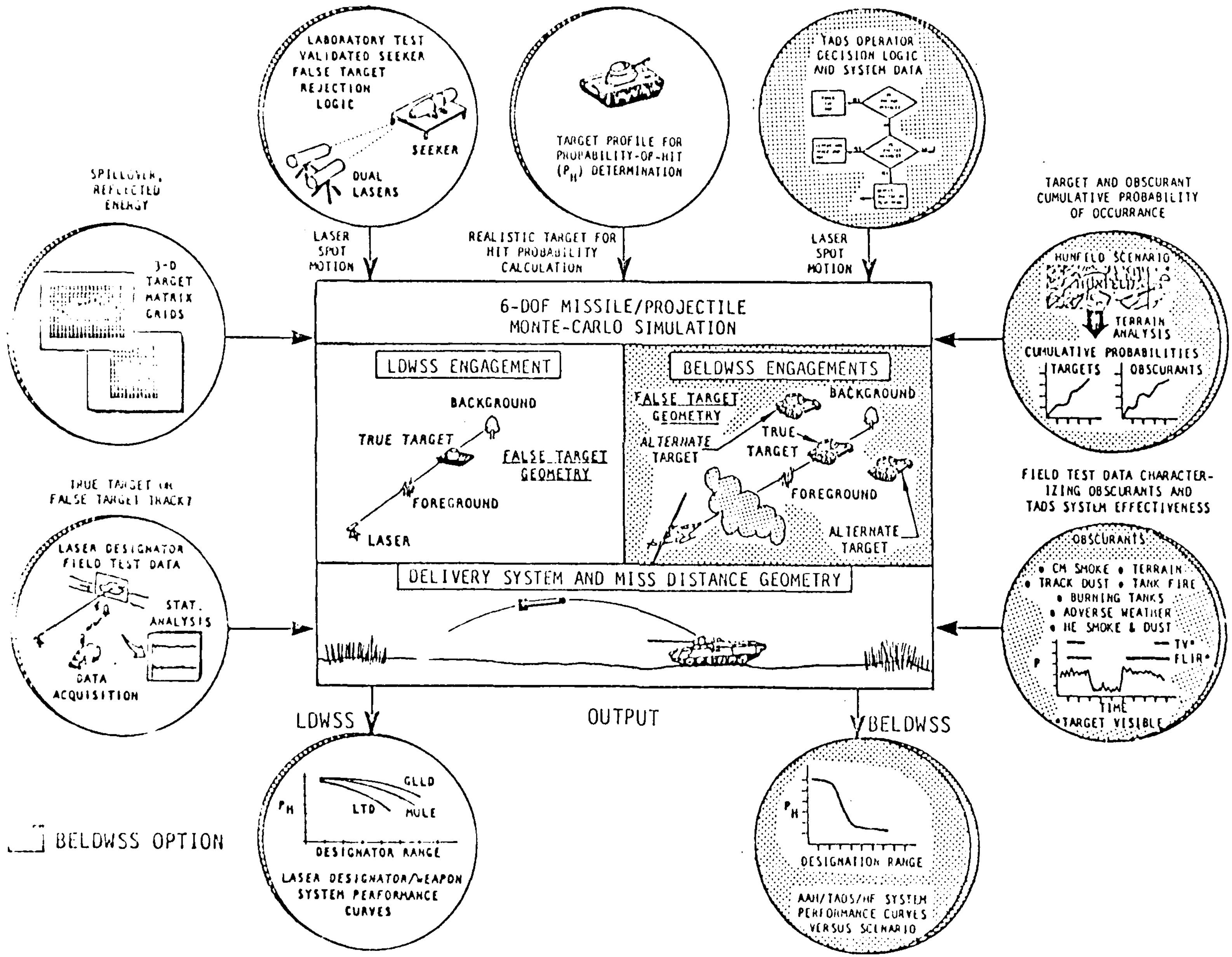

Figure 2. LDWSS/BELDWSS Integrated Weapon System Simulation.

TABLE 1

DATA REQUIREMENTS FOR THE BELDWSS TEST PROGRAM

AEROSOL CHARACTERISTICS

- Type/Number/Location/Timing of Submunitions
- Burntime/Persistence of Cloud
- Cloud Geometry/Location
- Aerosol Particle Size Distribution
- Aerosol Density Along LOS
- Aerosol Temperature
- Aerosol/Background Contrast
- Transmission at 4 Wavelengths Along LOS
- Laser Spot Centroid Position/Motion
- Backscatter Pulse Shape/Stretching
- Aerosol Phase Function

ENVIRONMENTAL CHARACTERISTICS

- Wind Speed/Direction/Shear
- Temperature/Slope
- Humidity/Dew Point
- Solar Insolation/Angles/Obscuration
- Cloud Type/% Coverage/Height
- Time
- Visibility
- Precipitation Kind/Rate
- Ground Cover/Soil Type/Moisture Content
- Barometric Pressure/Trend
- Atmospheric Structure Parameter

GENERATION OF MONODISPERSE DROPS

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St. Paul, Minnesota

Standardization and calibration of aerosol measuring instruments can best be accomplished by the use of monodisperse aerosols. The size, and sometimes the concentration, of the calibrating aerosol must also be known to a sufficiently high degree of accuracy. The quality of the calibration is often dependent upon the quality of the calibrating aerosol used and the accuracy to which the particle size and concentration are known. Figure 1 shows the size range of some of the commonly used aerosol size distribution measuring instruments, and the size range and other pertinent characteristics of the monodisperse aerosol generation techniques that can be used for instrument calibration.

Condensation coagulation is a generation method based on the rapid condensation of NaCl vapor in a cold air stream and the controlled coagulation of the resulting ultrafine aerosol.

The electrostatic classification method consists of generating a polydisperse aerosol with an atomizer and extracting particles within a narrow size range from the aerosol with a differential electrical mobility classifier.

Commercially available polystyrene and other latex spheres provide a relatively simple technique of generating a monodisperse aerosol of known size.

The vibrating orifice monodisperse aerosol generating technique is based on the instability and uniform break up of a liquid jet under periodic mechanical disturbances.

REFERENCES

Pui, D. Y. H., B. Y. H. Liu, "Aerosol Generation and Calibration of Instruments," Mechanical Engineering Department, University of Minnesota, TSI Quarterly, V, No. 2, 1979.

Agarwal, J. Gilmore Sem, TSI, Inc, TSI Quarterly.

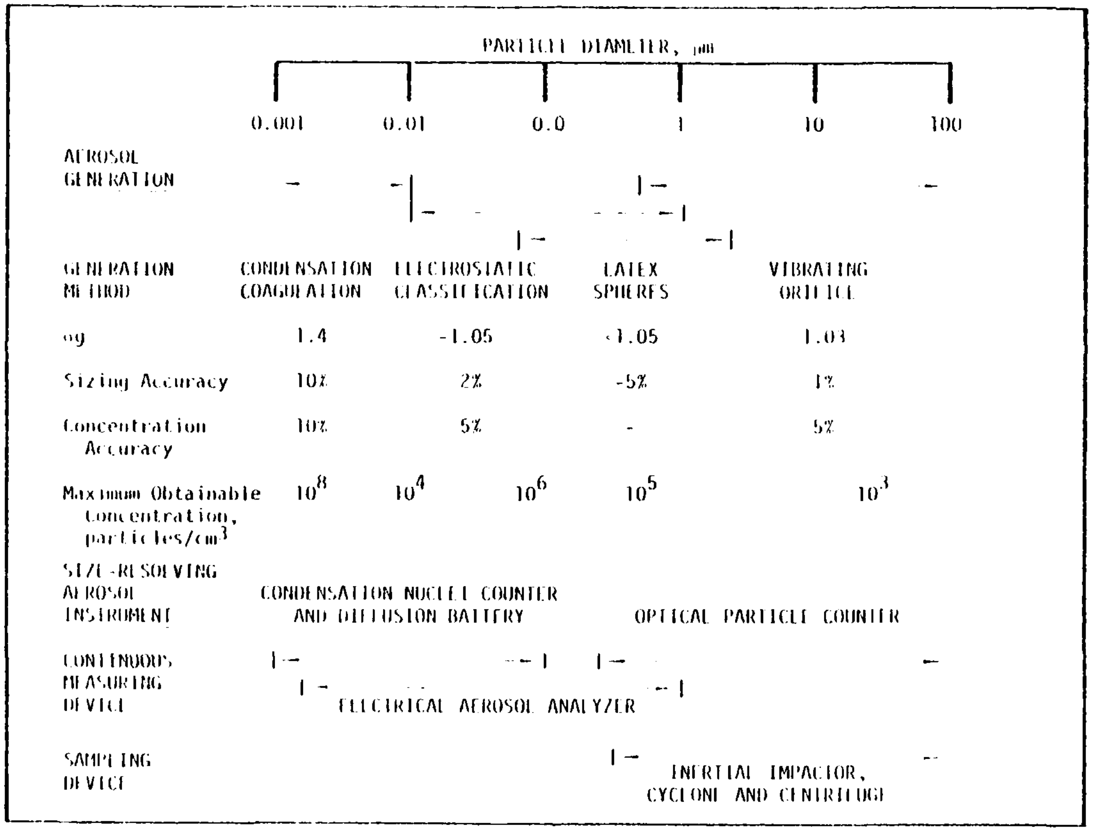

Figure 1. Size Range of Aerosol Generation, Measuring and Sampling Devices.

CALIBRATION AND SAMPLING CONSIDERATIONS IN PARTICLE SIZING

John Knollenberg
Particle Measuring Systems, Incorporated
Boulder, Colorado

The dominant problem in calibrating particle counters is the uncertainty in the sizes of calibration particles. A particular study (Porstendorfer) of commercial latex spheres was mentioned. It was found that the sampled particles had dimensions differing from their specifications.

Another calibration problem concerns correlating the scattering due to calibration particles with that due to an actual sample. Glass beads and water droplets scatter differently. A certain sized bead may scatter as a differently sized droplet. The relation between the sizes should be known for accurate calibration.

Figure 1 illustrates a typical calibration curve.

In making particle size measurements of a given aerosol sample, the experimenter must consider the following.

(1) How does the beam affect the sample?

(2) How is the sample obtained? Is it representative of the ambient volume? Have heavier particles been missed?

It was recommended that holographic and particle counter measurements be compared.

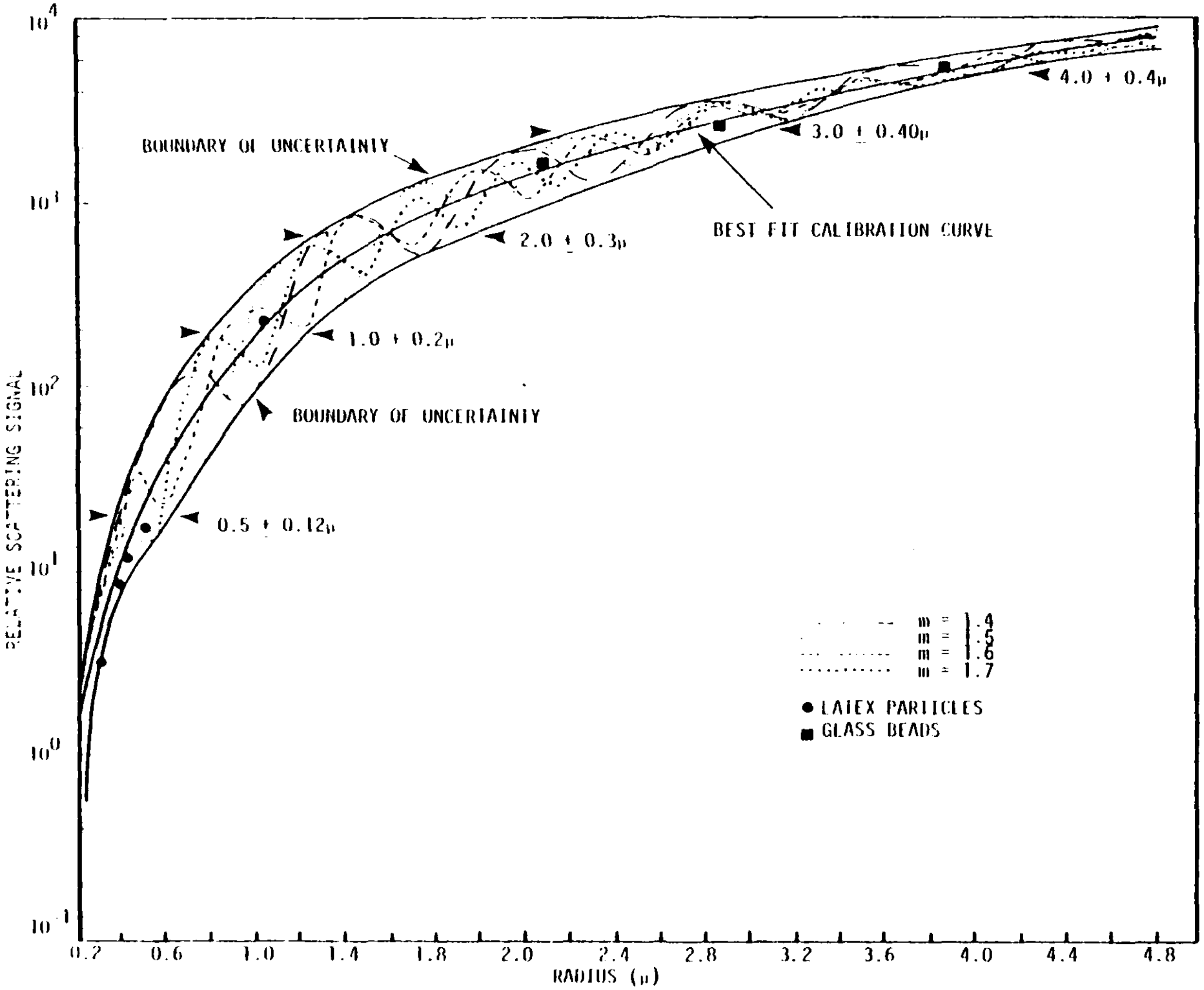

Figure 1. Typical Calibration Curve.

PARTICLE COUNTER CALIBRATION SPHERES

Shepard Kinsman
Coulter Electronics, Inc.
Hialeah, Florida

Dow Latex monosized spheres have been used for calibration of particle counters for a long time. These latices so far have not been available in sizes over 4 microns in monosized systems. Monosized calibration spheres of larger sizes are not available. Any size between 6 μm and 100 μm diameter can be made. The normal diameters marketed are: 5.0 - 10.0 - 15.0 - 20.0 - 43.0 - 90.0 μm. Determination of the sphere size as shown on the container label is a critical aspect of using calibration material. Kubitschek of Argonne National Labs has suggested an optical microscope procedure which forms rows of arrays of particles in a single layer on the microscope slide so that each measurement can include several particles instead of one particle. Three or four different types of measurements should agree with each other when dealing with spheres.

OPAQUE AEROSOL COUNTER INTERCOMPARISON

William Gallery
Air Force Geophysics Laboratory (OPI)
Hanscom Air Force Base, Massachusetts

A review of work on the intercomparison of various particle sizing probes used in the OPAQUE program was presented.

The intercomparison objectives included determination of size response, concentration prediction and wind effect on the instruments.

Test procedure involved "ambient" (indoor) and outdoor measurements.

Among the conclusions of the study were the following.

(1) Mean deviations in size definition were about 10-20%; maximum deviations from the nominal diameter were within 47%.

(2) Ambient measurements showed fair agreement in particle size but a number concentration or density which often differed (from the controlled value) by a factor of from 2 to 5.

(3) The direction or orientation of the instrument is important: distribution evaluations may be significantly affected with a probable discrimination against larger particles, in general.

(4) The previous discrepancies in measurements seem to have been due to misalignment of the optical probes.

REFERENCE

Cress, T. and R. Fenn (Editors), "OPAQUE Aerosol Counter Intercomparison - 25 April 1977 - 4 May 1977," AFGL-TR-78-0004.

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ATMOSPHERIC TRANSMISSION AND PARTICLE SIZE MEASUREMENTS, PROCEE--ETC(U)
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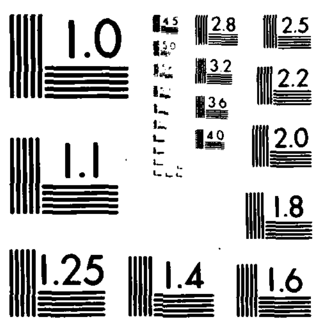

MICROCOPY RESOLUTION TEST CHART

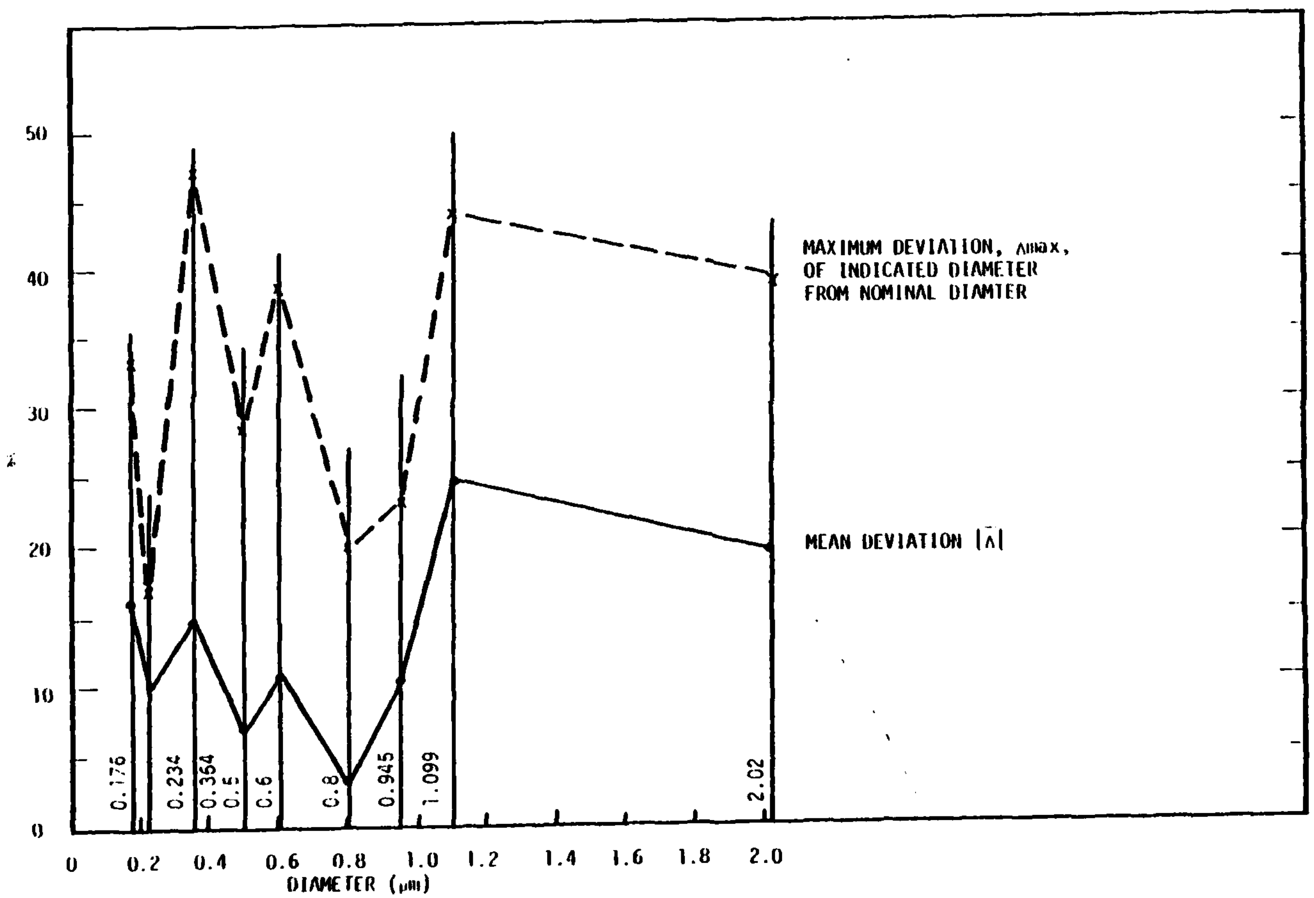

Figure 1. OPAQUE Aerosol Counter Intercomparison.

CALIBRATION OF KNOLLENBERG AEROSOL COUNTERS WITH WATER DROPLETS

J. E. A. Selby
Carl Weiser
Grumman Aerospace Corporation
Research Department
Bethpage, New York

Analysis was performed on two Knollenberg aerosol counters. A four-fold objective was defined as follows.

(1) Generate and measure sizes of monodisperse water droplets prior to their entry into the Knollenberg counters.

(2) Determine the response of the instruments to monodisperse water droplets of known size.

(3) Investigate the size of the active sampling areas of the probes.

(4) Investigate the depth of field of the probes.

The calibration results and conclusions for each counter are given (Figures 1 and 2). An overall summary is provided (Figure 3).

Recommendations for future work include the following.

(1) Use satellite water droplets to calibrate the ASSP-100 for the size range 5 - 20 μm.

(2) Calibrate the ASSP-100 number count by using satellite droplets.

(3) Check response of the ASSP-100 to variations in refractive index typical of maritime aerosols (SALT:H_2O solutions).

(4) Investigate the impact of Knollenberg measurement uncertainties on extinction.

MODEL NO:	Instrument Name and Description	Size Range (Dia. μm)
ASSP-100	Axially Scattering Spectrometer Probe	1.7 - 28.4

SUMMARY OF CALIBRATION

MEASURED DIA, (μm)	CHANNEL NUMBER	RECORDED DIA.*	FREQUENCY OF DROPS, Hz	ORIFICE DIA, (μm)
32.5	11 - 15	20 - 28.4	128	10
28.5	11 - 15	20 - 28.4	146	10
28.0**	11 - 12	20 - 24	159	10
23.5**	11 - 13	20 - 26	159	10

* Channel bandwidth approximately 2 μm

**Velocity reject circuit active

CONCLUSIONS
(ASSP-100 INSTRUMENT)

1. A given size droplet beam excites up to 5 consecutive channels.
2. As active sampling volume is traversed by droplet beam from left to right, the group of channels excited shifts from lowest to highest and back to lowest.
3. We could not generate useful droplets <23.5 μm with the TSI instrument.
4. We were not able to probe ASSP sampling volume (this would require a major mod of TSI droplet generator).
5. More work needed.

Figure 1. ASSP-100 Results.

MODEL NO:
OAP-200

Instrument Name and Description
Optical Array Cloud Droplet Spectrometer Probe

Size Range
(Dia. μm)
20 - 300

SUMMARY OF CALIBRATION

MICROSCOPE MEASURED DIA. (μm)	OAP-200 CHANNEL NUMBER	OAP-200 RECORDED DIA. (μm)	OAP-200 NO. DROPS/SEC RECORDED	DROPLET GENERATOR FREQUENCY OF DROPS, Hz	DROPLET GENERATOR ORIFICE SIZE (μm)	RUN NO.
104	5	94 - 113	18,000	18,000	50	1
103	4,5	74 - 113	37,500	37,900	50	A
102*	5	94 - 113	37,400	37,900	50	S1
93*	4	74 - 94	42,000	42,200	50	S2
33*	3,4	54 - 34	37,800	38,000	35	S3
68	3	54 - 74	27,000	27,200	35	2B
61*	2,3	34 - 74	---**	74,000	35	S4
60	2,3	34 - 74	---	53,600	35	7B
59	2,3	34 - 74	49,300	53,600	35	8B
52	2,3	34 - 74	35,000	35,000	20	3B
36	1	14 - 34	---	117,000	20	C3
25	1	14 - 34	---	152,000	10	D1
23	1	14 - 34	---	673,000	5	E

* Salt water droplets used

** Maximum counting rate of OAP-200 is 50,000 drops/sec

CONCLUSIONS
(OAP-200 INSTRUMENT)

1. Recorded droplet sizes to within the 20 μm manufacturers tolerance in all cases.
2. Recorded count rate agreed with measurements to better than 2% (within manufacturers stated frequency range i.e., <50 KHz).
3. Sensitivity of active sampling area was found not to be uniform
   e.g., it was  rather than  .
4. Depth of field was found to be ≤ specified value (i.e., one channel lower than specified).
5. As a result of 3 & 4 above, the active sampling area was found to be smaller than specified which leads to an underestimate of predicted number density by about a factor of 2.

Figure 2. OAP-200 Results.

1. OAP-200

- The OAP-200 was found to perform within its specifications for water droplets ranging in size from 23 to 104 μm diameter as regards number of counts per channel and size.

- Calculated number densities based on these measurements could be underestimated by as much as a factor of 2, because of the apparent non uniform sampling area.

2. ASSP-100

- An adequate calibration could not be performed due to problems in attaining small droplets and difficulties in interfacing the TSI droplet generator with the ASSP-100.

- Multiple channels are simultaneously excited by single monodisperse water droplets.

- The number of channels excited depends on position of droplets with sampling volume.

Figure 3. Summary of Analysis.

PARTICULATE SIZING PRECISION AND THE RELIABILITY OF SIZE DISTRIBUTION MEASUREMENTS

Henry A. Miranda, Jr.
Epsilon Laboratories, Inc.
Bedford, Massachusetts

The measured size distribution of aerosols can be seriously in error if any of several instrumental deficiencies delineated below are not scrupulously avoided. Some of the deficiencies to which particulate sizing spectrometers are prone involve subtleties that have remained obscure. Most of the deficiencies can be stated in general terms.

(1) Non-uniformity of illumination throughout the sensing volume.

(2) Sensing volume which is a function of the particle size (e.g., smaller particles not "seen" near the edges of an otherwise well-defined sensing volume, while larger particles detectable throughout).

(3) Output sizing pulses which depend upon geometrical parameters within the sensing volume, (such as, for example, their duration which in turn might affect the pulse height determination).

(4) Inadequate attention to the measurement of background levels.

(5) Statistical fluctuations in signal pulse levels.

The net effect of these deficiencies - or of any single one of these - is to distort the output in such a manner that the slope of the measured size distribution is less steep than that of the actual size distribution.

The observed system response to monodisperse particles is a most useful parameter for assessing the severity of this effect. In particular, the slope of the observed instrumental spread function (i.e., wings thereof) can be used as a quantitative measure to determine whether or not the measured size distribution is reliable. For example, whenever the slope of the latter is found to be comparable to that of the wings of the system spread function, this is an unmistakable indication that very gross errors have been injected into the measurements by one or more of the above type of system deficiencies. In order that the measured slope of the size distribution be useable without invoking complicated inversion techniques to recover the desired information from the raw data, it is necessary that the slope of the wings of the system spread function be at least one (and preferably two) orders of magnitude steeper than that of the actual particulate size distribution being examined.

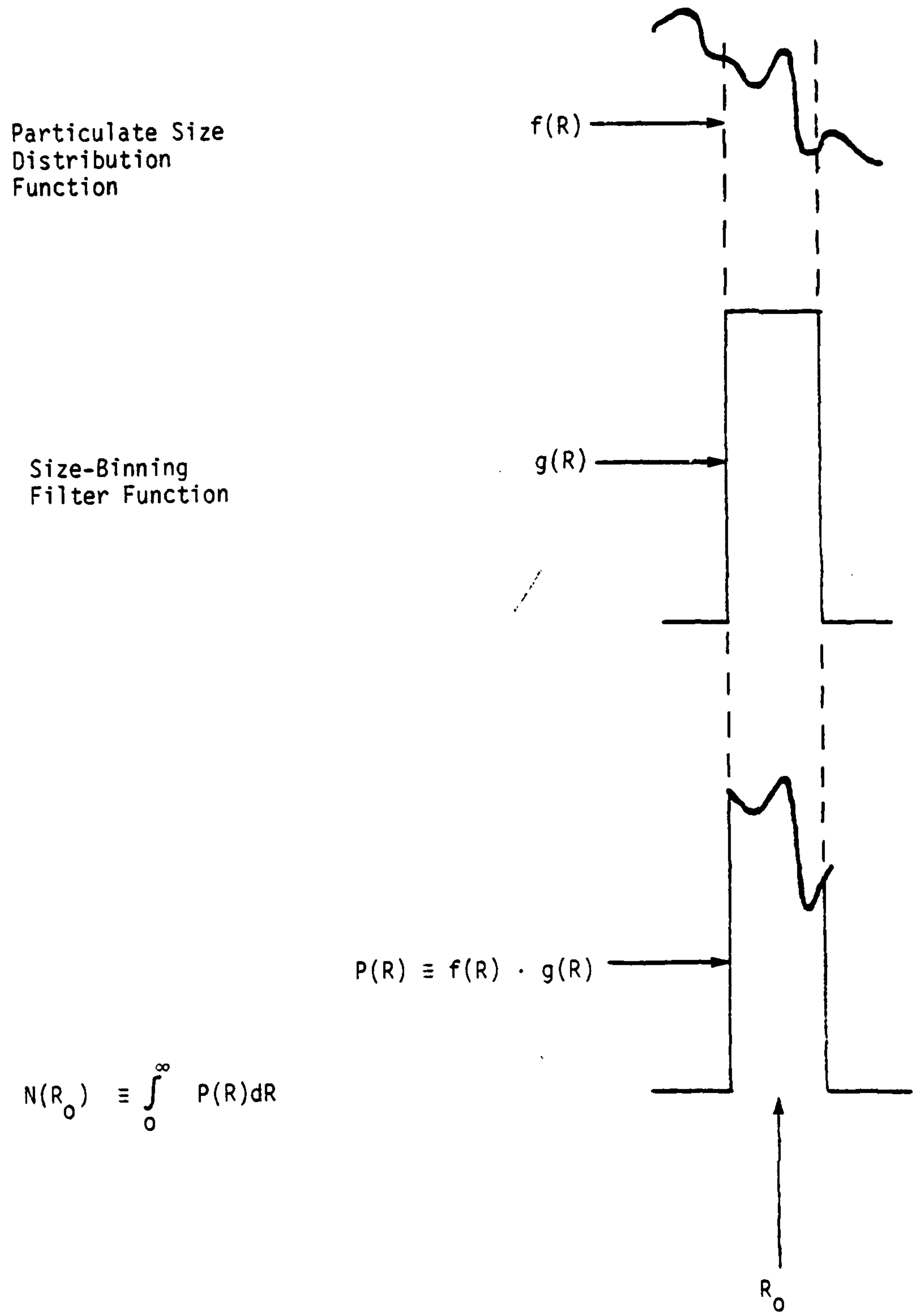

Figure 1. Action of Ideal Size-Binning Filter in Developing Particulate Output Count per Size Bin.

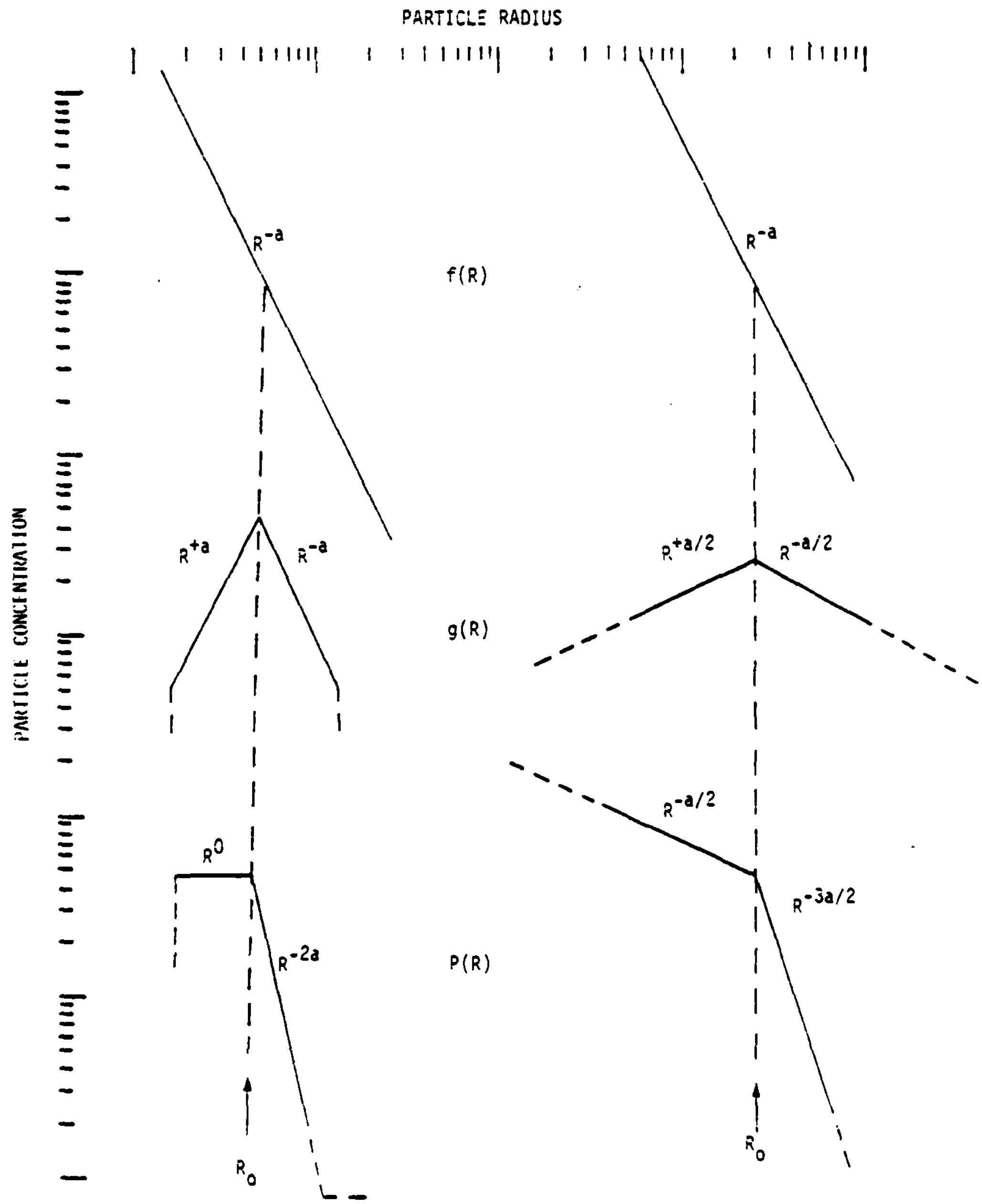

Figure 2. Idealized Effect of Filter Wings upon Size Distribution.

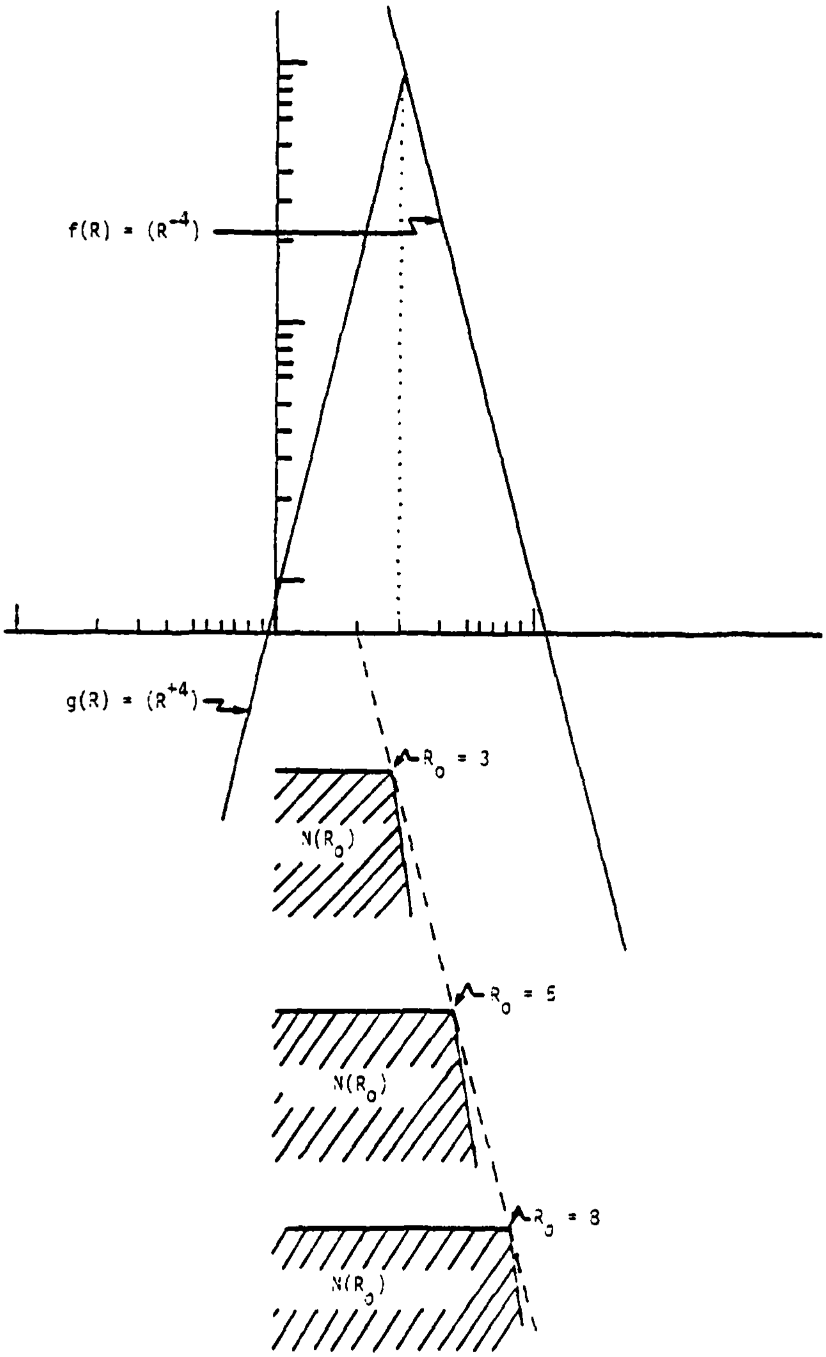

Figure 3. Specific Example of Filter Wing Effect, in Idealized Form.

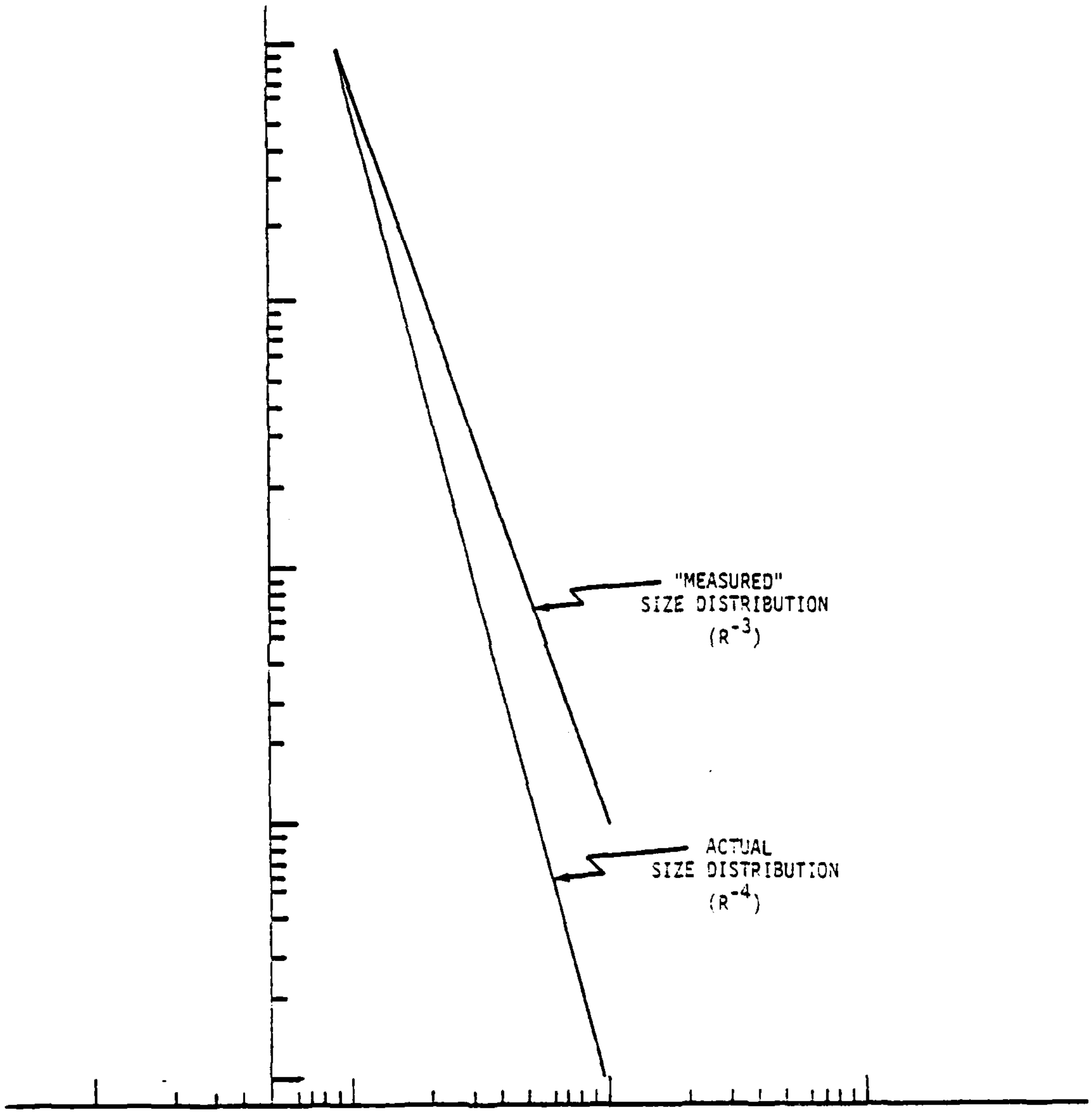

Figure 4. Schematic Illustration of Size Distribution Distortion by Filter Wing.

OPTICAL IMAGING TECHNIQUES FOR PARTICLE SIZE MEASUREMENTS

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The techniques of (conventional) high-speed photography and in-line pulsed holography, with regard to particle sizing, were briefly compared.

It was noted that the conventional approach with an optical microscope often confronts refraction problems which could lead to systematic errors. The effect has been observed for relatively small (7 μm) diameter particles.

Some practical findings for the holographic method include the following.

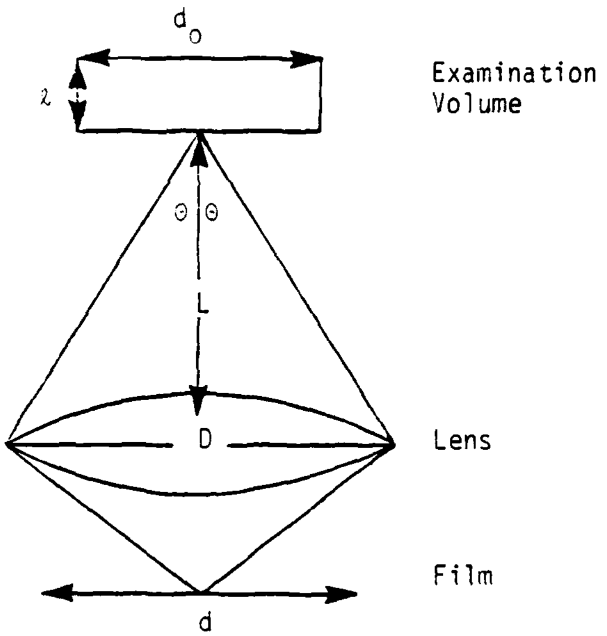
(1) Only drops in the depth of field are illuminated.

(2) A diameter measurement is readily obtained from the apparent "glint" separation.

(3) Diameter definition in the presence of refraction and diffraction effects is possible, however,

(4) A distortion on the particle surface or other nonuniformity of the droplet may degrade the measurement.

BASIC GEOMETRICAL CONSIDERATIONS FOR CONVENTIONAL HIGH-SPEED PHOTOGRAPHY



$$m \equiv \frac{d_i}{d_o}$$

$$F \equiv \frac{f}{D}$$

$$f = \frac{L}{1 + 1/m}$$

$$r = \frac{\lambda}{2F} \quad \frac{m}{1 + 1/m}$$

$$r > \frac{\lambda/2}{\sin \Theta}$$

BASIC GEOMETRICAL CONSIDERATIONS FOR IN-LINE PULSED HOLOGRAPHY

$$\frac{D/2}{L} > 4 \frac{\lambda}{a}$$

$$r > \frac{\lambda/2}{\sin \Theta}$$

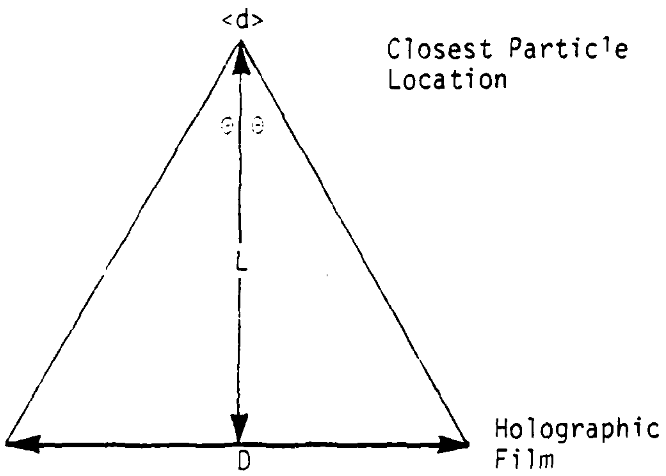


Figure 1. Geometrical Considerations.

PARTICLE FIELD HOLOGRAPHY AT
ARNOLD ENGINEERING DEVELOPMENT CENTER (AEDC)

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Holographic techniques have proven useful in the determination of particle sizes of ice droplets in flow fields. Certain of these techniques used at Arnold Air Force Base were discussed. Brief descriptions of the Subscale Icing Facility holocamera and its applications, as well as the AEDC Hologram Reconstruction System were presented.

Calibration of the system using a resolution chart at various positions in the neutral flow field was reviewed.

It appears that field measurements with the holographic technique are possible as in-flight holograms have been successfully made.

The accompanying figure gives an idea of the factors upon which quality of the in-line hologram depends.

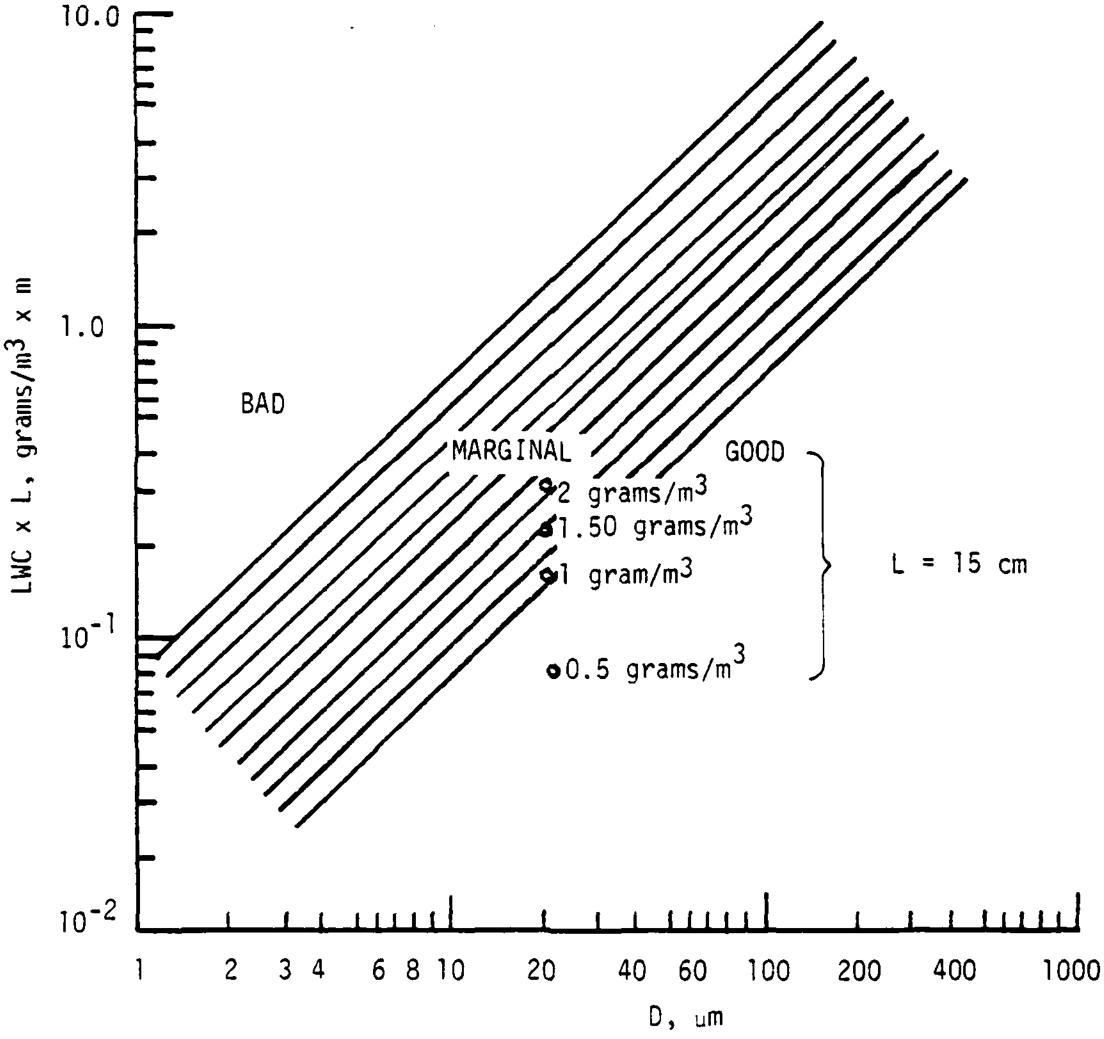

Figure 1. In-Line Hologram Quality Dependence on Liquid Water Content (LWC), Volume Depth (L), and Droplet Diameter (D).

LASER INTERFEROMETER FOR PARTICLE SIZE DISTRIBUTION STUDIES

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A particle sizing interferometer (PSI) measures the size of individual particles passing through a set of interference fringes by observing the visibility of the oscillation in the scattered light. A PSI was developed at Arnold Engineering Development Center to measure water droplet size distributions in a wind tunnel used for icing studies. Droplets were sized in situ in the range from 8 to 80 micrometers while droplet velocities in the air flow exceeded 100 meters per second. Number densities ranged up to a few hundred per cubic centimeter. Details of the design have been published elsewhere (Reference 1).

A laboratory evaluation of the PSI was made subsequently using oleic acid droplets produced by a Berglund-Liu monodisperse particle generator. Figure 1 shows a size distribution histogram obtained for five different monodisperse streams produced. Particles with diameters 5 microns apart were easily resolved. The scattered light was observed in the on-axis forward direction.

Anomalies in wind tunnel data indicate that number densities in the tunnel flow may have been too high for observing single droplets. Laboratory work is being directed toward light collection from several degrees off-axis in the forward direction in order to effectively decrease the observation probe volume and thus reduce the occurrence of multiple particle observation.

REFERENCE

Roberds, D. W., Optical Engineering, 18, 236 (1979).

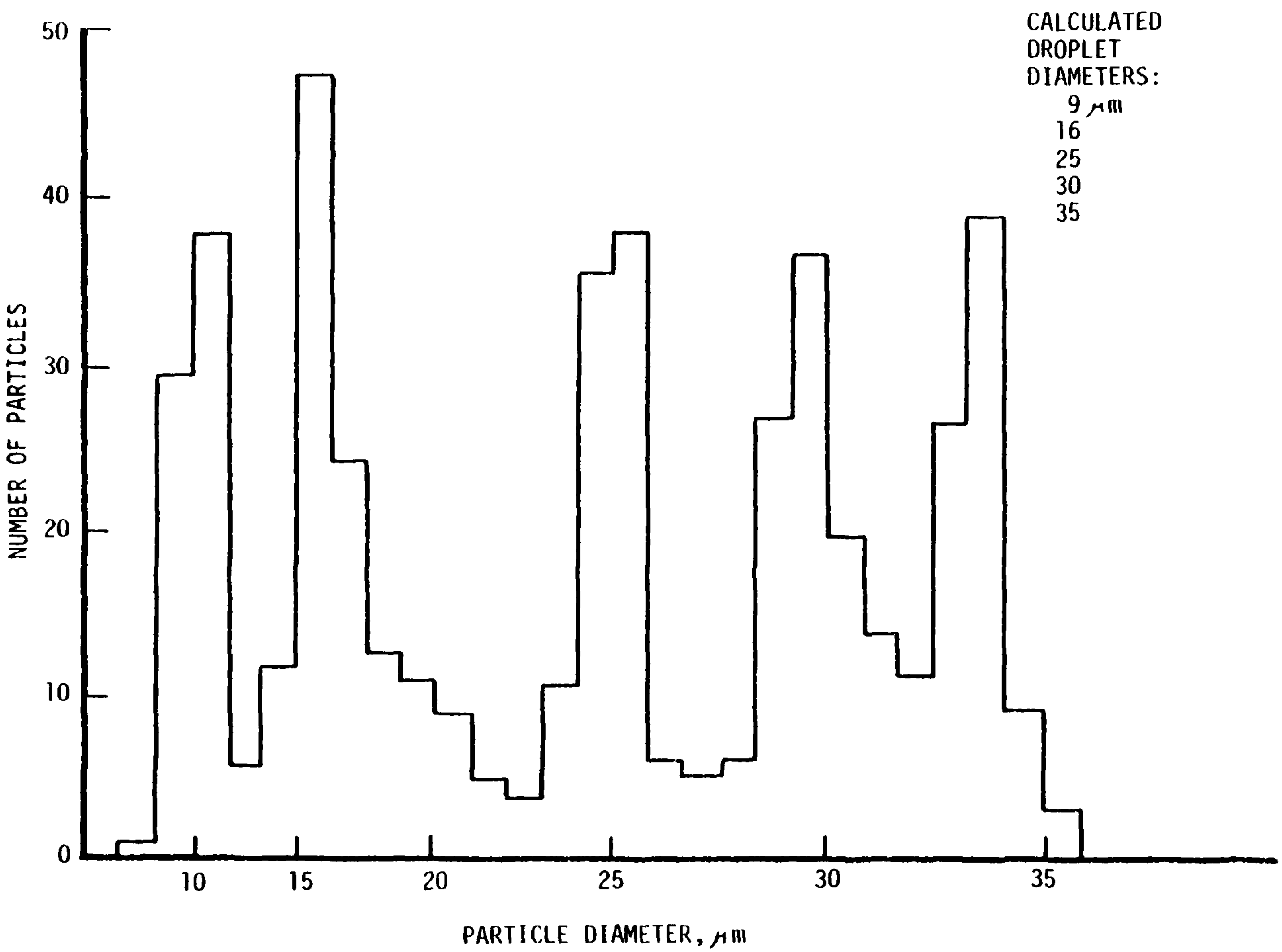

FIGURE 1. Size Distribution Measured for Five Different Monodisperse Droplet Streams

IN SITU CHEMICAL ANALYSIS OF INDIVIDUAL AEROSOL PARTICLES

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The majority of existing experimental approaches to the determination of aerosol composition have two major problems in common, specifically, the failure to establish that:

(1) no interaction among the various materials sampled takes place immediately following the collection procedure and that contamination by the sampling device is nonexistent; and
(2) there is no guarantee that chemical reactions may not occur between the time of particulate sampling and post flight chemical analysis.

Many theories as to the complex chemical interactions of the (upper) atmosphere have been developed over the years -- all of which are initially dependent upon knowledge of the size concentration and distribution, basic chemical composition and various other parameters -- none of which are known to a high degree of accuracy. A new instrument, which is in an intial breadboard study phase, may permit a definitive solution to some of the existing problems.

The design of the following instrument is of a proprietary nature and is the subject of a Patent Application by Epsilon Laboratories.

Ambient air is sampled through a 1 millimeter I.D. flow tube under laminar flow conditions. A gap in this tube is illuminated by a ribbon-shaped beam of 6238 Å HeNe laser light in a direction perpendicular to the sampling flow. As aerosol particles pass through the sensing gap, the resultant scattered light is collected by two separate annular optical channels and detected with individual photomultipliers. The signal output pulses have a typical duration of about 60 microseconds corresponding to a particle transit time across the illumination beam, which is about 0.3 millimeters in width.

Output signals from the twin photomultipliers are amplified logarithmically and digitally recorded on nine track magnetic tape which is IBM 370 computer compatible.

Following the detection and sizing of an individual aerosol particle, appropriate decision circuitry (which processes signal output pulses from the aerosol spectrometer to establish particle size thresholds) is used to trigger a small pulsed CO_2 laser operating at 10.6 microns which vaporizes the particle. The vapor cloud thus generated is illuminated by a pulsed Xenon flashtube and the resultant scattered light flux is detected by the employment of an ultraviolet transmission grating configured as a slitless spectrograph. The spectra obtained is then recorded by photographic or other suitable means for subsequent spectral analysis and chemical identification.

The possibility of detecting and identifying a relatively large number of constituents of the atmosphere is shown in Table 1. This partial listing, along with selected characteristic spectral signatures which might provide a means of molecular identification, gives some indication of the potential value of this device.

While the instrument as described is specifically designed for use in the upper atmosphere, the basic design principles should be equally valid for ground level and lower atmosphere exploration as well. In this connection it cannot be emphasized too strongly that any hope of correlating in situ ground measurements of aerosol size distributions with integral line-of-sight transmission and/or scattering measurements rests upon knowledge of the index of refraction of the scattering centers. This, in turn, is dependent upon a knowledge of the chemical constituency of individual aerosol particles - data on which, at present, are virtually nonexistent.

Because of an inherent sensitivity to the index of refraction of particulate materials, optical sizing instruments do not generally measure the true particle size. While careful instrument design parameters may be chosen to alleviate this difficulty, it is present to a greater or lesser degree in all instrument designs and is a complex function of particle size and index of refraction, light source characteristics, and detection angles. The existing AFGL/Epsilon sizing spectrometer partially overcomes this problem by employing twin optical channel detection, presently at 10 and 30 degree angles. The ratio of signals from these two channels is appreciably less sensitive to refractive index error than is obtainable by more conventional single channel systems. Signal to noise ratios, however, limit this technique to the larger particle sizes.

The development of the described particle composition analysis device would permit a measure of the index of refraction of an individual particle. By iterative processing, this information may be used as a correction factor to essentially eliminate the present sizing uncertainties due to refractive index dependence.

The present aerosol spectrometer is capable of sizing particulates from about 0.25 to 1 micron diameter. Preliminary calculations indicate that extension of small particle measurement capability could go to 0.1 and possibly as small as 0.05 micron diameter.

TABLE 1

ATMOSPHERIC CONSTITUENTS

SPECIES	RESONANCE TRANSITION SPECTRAL REGION	REMARKS
SO_2	1900-2300 Å 2600-3400 Å	Several discrete bands in these two regions
CO_2	<1850 Å	
H_2S	1900-2700 Å	Broad continuum
H_2CO	3530; 3430; 3390; 3370; 3295; 3260 Å	
NH_3	<2168 Å	At elevated temperatures, some "hot" bands appear at 2431 Å
	8370 Å	Distinct band
NO_2	4555 Å and 4352 Å	Irregular, ill-defined structure
	3910 Å	Diffuse region
	7500 Å	Strong absorption band
HNO	5500 Å	Weaker bands
H_2O	1450-1860 Å	
NaCl	3030 A-5540 Å	
HCl	2300 Å	
HCO_2	3300 Å-4400 Å	
ClO	3620 Å	
CH_4	<1500 Å	

PARTICLE SIZING NEEDS/PROBLEMS OF JET ENGINE TECHNOLOGY

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There are critical needs for particle size measurements in jet engine technology. These include applications in:

(1) the design of fuel nozzles (for emission and performance evaluation);

(2) the design of spray nozzles used to simulate rain and ice aerosols for laboratory measurements at the engine inlet; and

(3) measurement of particulates in smoke and gaseous emissions.

Typical measurements involve droplet sizes (10-200 μm range), concentration and spatial distribution.

INSTRUMENTATION AND THE STATE OF THE ART OF PARTICLE SIZE MEASUREMENTS

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A brief review of recent developments in particle sizing instrumentation and techniques was presented. Among the new (optic-acoustic) devices/methods discussed are as follows.

(1) Laser Velocimeter. The University of Arkansas has experimented with such a velocimeter for application to industrial stack measurements. The laser drives particulates within a chamber. Monitoring a simultaneous acoustic signal for frequency lag enables discrimination of particle sizes.

(2) A spectrophonic technique developed by the General Motors labs can be used to measure emissions. The acoustic signal from particles traversing an infrared laser beam can be pulse analyzed to reveal size information of diesel soot.

The following comments pertinent to the state of the art of particle sizing were offered.

(1) A serious problem for measurement devices is the lack of particle sizing standards. The NBS does not, at present, set standards. It has, however, recently begun a program which should determine and coordinate the efforts needed to establish such standards.

(2) Optical counters give size and concentration in terms of calibrated particles (typically, latex spheres). Oddly or imperfectly shaped particles may thus give misleading measurements.

(3) Reliable particle size measurements require knowledgeable, experienced personnel as well as realization of instrument limitations.

(4) Measurement fidelity can often be checked by dyeing an aerosol and comparing the collected sample with the measured expectation. A similar use of a radioactive tracer may also test measurement reliability.

APPENDIX C

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